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TECHNOLOGY SURVEY

Volume VII: Characteristics of

Metals That Influence System Safety

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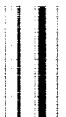
TECHNOLOGY SURVEY

Volume VII: Characteristics of

Metals That Influence System Safety

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PREFACE

This document is one of a series of publications being developed by the NASA Aerospace Safety Research and Data Institute for use as oxygen system design and operation guidelines. This Special Publication reviews the major issues in the safety and reliability of metals usage in oxygen systems and is presented as a descriptive summary covering these issues.

A microfiche supplement of references is attached inside the back cover to make pertinent pages of listed references readily available to the reader. Some references are included in their entirety, while only selected pages or sections of others are reproduced. Commonly available handbooks and copyrighted textbooks are not included in the microfiche supplement. The location of each reference in the microfiche supplement is noted in the list of references at the end of the report.

This review recognizes the cost in time and dollars that results from any system failure regardless of the cause. Although oxygen initiated failures are emphasized, all types of failures are considered since the results of oxygen system failures are generally more serious because of the chemical and physical properties of the oxidizer.

A second objective of this volume is to bring together available information that will help define the limiting conditions of use that oxygen "compatible" materials may be expected to withstand when used in oxygen systems.

The following representatives at the NASA centers and at the National Bureau of Standards participated in the critical review of the text: Melvin G. Olsen of the Kennedy Space Center; Robert L. Johnston and Glenn M. Ecord of the Johnson Space Center; James H. Hess of the Marshall Space Flight Center; John M. Kazaroff and George Tulusiak of the Lewis Research Center; and Alan F. Clark and Jerome G. Hust of the Cryogenics Division, National Bureau of Standards.

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iii

CONTENTS

SUMMARY

This report contains the results of a literature survey and analysis of the material and process factors affecting the safety of metals in oxygen systems. In addition, the practices of those who specify, build, or use oxygen systems relative to the previous is summarized. Alloys based on iron, copper, nickel, and aluminum were investigated representing the bulk of metals found in oxygen systems. Safety-related characteristics of other miscellaneous metals are summarized.

It was found that factors affecting the safety of metals in oxygen systems exist in all phases of the evolutionary process, from smelting and mill techniques through end-product fabrication.

The interplay of safety-related material and process factors became most complicated when iron alloys (steels) were considered, because of the existance of multiple metallurgical phases. Aluminum, although widely used in oxygen systems, can liberate relatively large amounts of heat in an oxygen fire. Nickel is highly fire resistant and easily fabricated, but it is too expensive and limited in availability for extensive use. Copper is also highly fire resistant, but lower strength and fabrication difficulties curtail its use in large structures.

Steels, due to large available property ranges, are found in the construction of all kinds of oxygen system components including gears, shafts, plumbing, tankage, and fasteners; aluminum is used principally in tankage and forged parts such as valve bodies; nickel is used in more critical (high pressure, high temperature) applications as lines and cast and forged components; and copper is found in small oxygen components as castings, forgings, and wrought shapes in the form of low pressure tubing, springs, valve components, and gaskets.

Of the miscellaneous metals, magnesium, titanium, and beryllium are distinctly hazardous because of the ease and severity of reaction or because of the toxicity of the reaction products. The metals gold and platinum are exceedingly safe due to their high stability against oxidation.

The safety of a given metal in an oxygen system was determined to be influenced by the particular service requirement. The metal characteristics should favorably influence fulfillment of these requirements. Thus, no singular metal or alloy could be classified as safest for all types of oxygen service.

INTRODUCTION

This survey examines the properties and characteristics of technically important metals and alloys as influencing factors in oxygen system safety, complemented with a summary of prevailing practices with these metals and alloys in oxygen systems. The reader is thus (1) exposed to the types of engineering considerations he would have to make when selecting a metal for oxygen service, and (2) provided with the "metal selection practice" of the technical community with which to substantiate his selection.

The vulnerability of an oxygen system to fire or hazardous mechanical malfunctions is in part influenced by the physical characteristics of the metals used herein. For example, oxygen, in common with all cryogenic liquids, can cause certain metals to be brittle, facilitating failure. Pressure burst in a high pressure gaseous oxygen system can likewise be affected by some characteristic in the containment metal (such as low toughness) resulting in a bomb-like explosion. Fires often result when metal failures occur because (1) the rate of energy release is very high when highly stressed metals fail, (2) fragmentation and impact sometimes occur, and (3) other, perhaps less compatible, portions of the structure or surroundings are suddenly exposed to oxygen. Oxygen can produce other effects on structural metals, but these effects are of little consequence to the engineer. For example, the fatigue resistance of certain metals, typically nickel alloys, is lowered by the presence of oxygen. This effect is, however, produced by the presence of only 0.01 millimeter mercury oxygen partial pressure in the environmental gas; concentrations in excess of this have no further effect (ref. 1). As a further example, oxygen by itself is not corrosive to structural metals, and because of the necessity for internal system cleanliness to minimize fire hazards, sufficient containment is not typically present inside the system to induce corrosion. Emphasis is therefore placed on the threats mentioned in the previous paragraph; namely, metal fires and metal rupture (principally brittle fracture).

Four basic alloy systems commonly used in oxygen systems are discussed: steels, aluminum and aluminum alloys, nickel and nickel alloys, and copper and copper alloys. A summary of more exotic metals is also provided.

For each alloy system, the basic influencing properties are discussed. The effect of alloy composition and processing variables on these properties is shown.

For each alloy system, the prevailing metal selection practice of those who specify, build, or use oxygen systems is summarized. This information includes codes, use restrictions and limitations and reasons therefore (if known).

It should be noted that not all pertinent issues on oxygen safety are discussed for each metal. This would make the report repetitous. The issue is raised at the first opportunity and only repeated if it is vital to the alloy being discussed. Table I is presented as a guide to determine the relevancy of various considerations to various metals in oxygen system service.

TABLE I. - RELEVANCE OF ISSUES TO METALS

[1, usually irrelevant or of little concern; 2, should receive attention depending on application; 3, should receive attention at all times; 4, very important, always a potential contributor to hazard; 5, critically important, principal contributor to hazard.]

Issue	Alloy				
	Steel	Alumi-num	Nickel	Copper	Miscel-laneous
Brittle transition	5	2	1	1	2
Strengthening	5	2	3	4	2
Casting	2	2	1	2	2
Welding	3	4	2	N/A[a]	N/A
Forging	3	3	3	3	2
Surface smoothness	3	4	2	2	2
Thermophysical properties	2	4	3	3	3
Code and use history restrictions	4	2	3	3	3
Plating and passivating	3	1	2	1	2
Lubrication	3	1	1	1	2
Tolerance to contamination	5	5	4	4	4

[a]N/A, not applicable.

BRITTLE FRACTURE OF METALS - BASIC INFLUENCES

Any system is subject to inadvertent overloads. The behavior of the system to an overload may be tolerance or failure. The behavior of structural components under overload situations can be divided into three categories: (1) where yield of the structure relieves the overload and rupture does not occur, (2) where yield of the structure does not relieve the overload and rupture occurs, and (3) where yield of the structure constitutes failure in itself regardless of rupture. Examples of (1) may be bolts in bolted joints, struts, and closed containers completely full of pressurized but incompressible fluids. Examples of (2) are all pressure vessels containing compressible fluids such as lines, fittings, and tanks, and rotating components subject to centripetal loads such as pump impellers, etc. Examples of (3) are bearing surfaces, gears, cams, etc. Category (1) is a forgiving situation. Category (3) involves prevention of yield failure by providing high yield strength, often at the sacrifice of toughness. In oxygen systems, category (2) is the condition for potential explosion compounded by fire, the most common and severe hazard. The behavior of metals in this category (2) situation and the resultant safety is the subject of this section.

Capacity to Absorb Energy

Toughness is the ability of a metal or alloy to absorb mechanical energy prior to
rupture. The most important singular factor in the selection of materials for items such
as pressure vessels is to assure that toughness (and, to be discussed, ductility) is inher-
ent in the material at all use temperatures. A tough material will resist failure by de-
forming plastically (yielding) when subject to substantial amounts of energy as illustrated
in figure 1. Conversely, a low toughness material, although usually much stronger, will
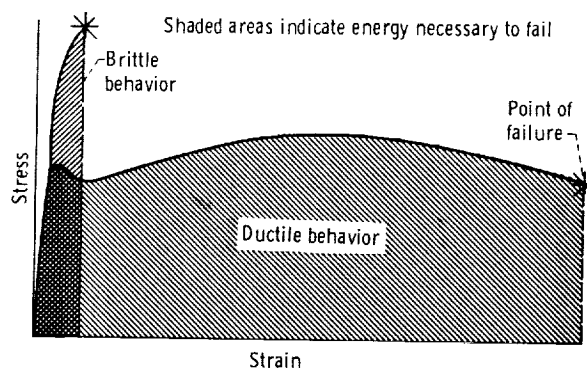
Figure 1. - Ductile and brittle behavior.

fail with little or no plastic deformation when subject to smaller amounts of energy
(ref. 2, pp. 188 and 189). Energy can be supplied from abrupt pressurization, inadver-
tent impact, thermal shock, etc. While a pressure vessel should not intentionally yield
in service, it should yield before rupture rather than rupture in a low toughness mode in
the event of an overload. The reason is simple: the energy contained in the fluid is par-
tially absorbed in the plastic deformation of the vessel which reduces the energy of the
explosion.

Fracture Mechanics Considerations

All structures contain flaws either introduced during fabrication (such as welding
porosity, gas bubble formation during mill operations, etc.) or during operation (cracks
generated from cyclic stressing, cracks generated from stress corrosion, surface nicks
from impact, etc.). Structures occasionally fail at stress levels far below the yield
strength, where the failure initiates at some flaw site. What has happened is that local-
ized yielding in the region of the flaw was prevented and the stress across the flaw had
to be absorbed by the flaw tip causing the material at the flaw tip to fail. If the load is

4

not released by this action, the flaw will further progress and, because progressively smaller amounts of sound material are left, the process will continue in an unstable manner until the component separates. If, on the other hand, the material at the flaw tip could flow plastically to relieve the local stress, the flaw would not extend and failure would not occur. The previous separates ductile from brittle behavior in metals. Ductility is therefore the ability of the material to deform plastically while toughness is the ability to absorb energy during plastic deformation. Ductile to brittle transition in a particular metal is facilitated by high strain rates (impact), decreasing temperature, and a state of complex stress acting to constrain the material. A liquid oxygen pressure vessel embodies all of the conditions necessary for brittle explosion: low temperatures, the existence of a compressible fluid, a state of complex constraining stresses in the vessel wall, and the potential for sudden overload (impact or internal reaction).

Effect of Crystal Structure

The ductile or brittle behavior of metals is dependent on the structure of the crystals contained therein. Metals with cubic lattice structure and one atom in the center of each face (FCC) show no loss in ductility down to at least liquid oxygen temperature. Examples are aluminum, copper, and nickel. Metals with cubic lattice structure and one atom in the center of each cube (BCC) and metals with a hexagonal crystal structure show a marked ductile to brittle transition. Examples are iron, carbon steel, and titanium. Fortunately, iron can be alloyed in a way that the ductility improves. One can never rely on the previous criterion as the only one for predicting the ductile or brittle behavior of a given metal because other metallurgical factors are also at play in a real alloy system. For example, dissolved gases, metallic precipitates, grain size, and component size also have relevance in ductile or brittle behavior as evidenced in the following sections.

Effect of Elevated Temperature

Certain alloys sustain a loss in ductility as the temperature is raised to a substantial fraction (one-quarter to three-quarters) of the melting temperature. This is evidenced by a loss of elongation of metal samples in tensile testing. In an oxygen system, should a heat-producing reaction occur that would elevate the temperature of a pressure containment structure, a brittle failure of this otherwise ductile structure could occur. This is especially serious if the alloy sustains a loss of ductility before it sustains a loss of strength with increasing temperature: this prevents failure in a ductile mode by loss

of strength due to heating. Paradoxically, those alloys that exhibit a high degree of ductile behavior at cryogenic temperatures generally suffer a loss of ductility at high temperatures. Examples of alloys that lose substantial ductility before losing substantial strength at high temperatures are Inconel X-750, Monel K-500, and nickel silvers. Examples of alloys that lose ductility and strength more or less simultaneously are austenitic (300 series) stainless steels, brasses, and bronzes. Examples of alloys that do not lose ductility (or, in some cases, gain ductility in a continuous manner) are low alloy steels, martensitic (400 series) stainless steels, Inconel 718, Hastelloy X and, apart from the aforementioned paradox, copper and aluminum alloys.

STEEL

Steels comprise the most widely used group of alloys in oxygen systems because of their diversity of properties, low cost, and ease of fabrication. Reference 3, in a review of applicable literature, has concluded that ignition of steels in oxygen generally occurs near the melting temperature of 1300° C. Combustion is continuous and moderate, intermediate between nickel alloys (which gradually quench) and aluminum alloys (which burn vigorously). At 800 psi the ignition temperature for low alloy steels is lowered 200° to 400° C below the melting temperature and the burning rate is increased. The ignition temperature of steels is probably further lowered at still higher pressures

TABLE II. - BASIC FACTORS AFFECTING THE SELECTION OF

STEEL FOR OXYGEN SERVICE

Carbon steel	For - The cost is low and ease of fabrication in large commercial ground structures. Good strength exists considering cost. Against - Surface scales (rust) form with moisture creating a potential contamination trap. These scales can also be carried in the fluid stream to initiate reactions elsewhere in the system. Ductility is lost at subzero temperatures prohibiting pressure containment of LOX.
Alloy steel (high-strength, low-alloy steel)	For - Such alloys possess exceptional hardness and strength for wear resistant surfaces and containment of high pressure gaseous oxygen. Against - Same as Carbon steel.
Stainless steel	For - Retention of ductility at LOX temperatures (austenitic grades only) permits containment of LOX. Only a very thin oxide film forms which facilitates cleaning and minimizes contaminant accumulation. Against - The cost is higher than for others. The strength is lower than alloy steels.

by virtue of the observed trend at lower pressure ranges. Reference 4 (pp. 32 to 34) indicates that the ignition of steels can be promoted easier than the ignition of copper or nickel at 7500 psi. Combustion characteristics for various steels will differ if the alloying elements chromium or nickel are present in large (>10 percent) amounts. Chromium (such as in 400 series stainless steels) will invigorate the combustion, and nickel (such as in 300 series stainless steels) will passify the combustion. Selection criteria are shown in table II.

Application in Oxygen Systems – Alloys Suitable for Use

Table III (from refs. 5 and 6) lists the uses for steel in oxygen systems and the

TABLE III. – SELECTION OF STEELS FOR USE IN OXYGEN SERVICE[a]

Applications (with reference to text)	Major factors influencing selection	Steels commonly used in oxygen service
		Service temperature extremes, °F 500 80 -20 -75 -170 -300
Category I – Pressure vessels: lines, fittings, valve bodies, tanks, etc.	Notch impact toughness Fracture toughness Notch strength Thermal shock resistance Creep resistance Weldability Formability Avoidance of phase-transformation-induced brittle behavior Ability to provide smooth surface finishes – resistance to surface corrosion Fire compatibility with oxygen Resistance to stress corrosion	Carbon, alloy steels LOX Carbon, alloy steels Controlled C-Mn ratio $2\frac{1}{4}$ Ni steel $3\frac{1}{2}$ Ni steel, 12 Ni maraging 9 Ni steel 304 stainless steel 304L, 316, 318, 321, 347 stainless steel 310 stainless steel
Category II – Load bearing surfaces: bushings, rolling-element bearings, gears, pivot-joints, shafts, etc.	Hardness High modulus Fatigue strength Dimensional stability Machinability Acceptance of phase-transformation-induced brittle behavior to improve performance Ability to provide smooth surface finishes – resistance to surface corrosion Fire compatability with oxygen Resistance to stress corrosion Compatibility in oxygen when lubricated Resistance to galling, seizure	440C stainless steel Incoloy alloy 802 52100 Nitralloy 135 modified D6A M50
Category III – Locating hardware: fasteners, struts, ties, brackets	Strengthenability by thermomechanical treatments Creep resistance Formability Compatible thermal expansion characteristics Ability to provide smooth surface finishes – resistance to surface corrosion Fire compatibility with oxygen Resistance to stress corrosion Compatibility in oxygen when lubricated Resistance to galling, seizure	301, 302 stainless steel 410 stainless steel 17-4 PH, 17-7 stainless steel AM350 stainless steel A 286

[a]From information in ref. 5 (pp. 63 to 536) and ref. 6 (secs. 11XX to 16XX).

types of steels to fulfill these uses. There are over 500 alloys classified as carbon steels, alloy steels, high strength steels, and stainless steels as listed in reference 7 (pp. 1 to 14). Each of these alloys has certain properties which permit specific uses in oxygen such as those listed in table III. Engineering considerations such as welding, machining, forging, and casting for most of these alloys are given in reference 5 (pp. 63 to 536) and are not summarized here because of the extensive volume of such information.

Phase Transition and Brittle Failure of Steels

The three basic factors that contribute to brittle behavior in a given steel are high strain rates (impact), low temperatures, and the presence of notches (fig. 2 from ref. 8,
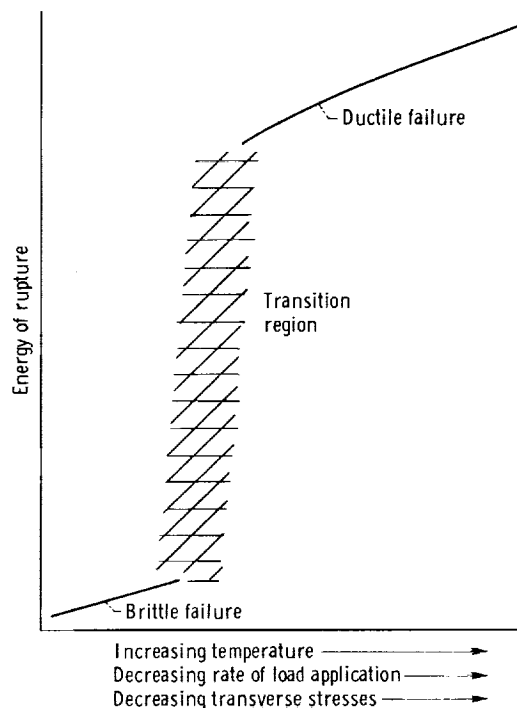
Figure 2. - Effect of temperature, rate of loading, and transverse stresses on type of failure (ref. 8, p. 17).

p. 17). According to present knowledge, there is always a considerable increase in yield strength with a corresponding loss in ductility at high strain rates; the yield point for mild steel doubles for an increase in strain rate from 10^{-3} to 10^{2} inch per inch per second. At some point in decreasing temperature, called the nil ductility transition

8

TABLE IV. - MINIMUM ACCEPTABLE IMPACT VALUES FOR STEELS[a]

Material	Specified minimum tensile strength	Operating temperature range, °F		Charpy V-notch impact energy, ft-lb		Lateral expansion, in. (mil)
				Fully deoxidized steel	Other than fully deoxidized	
Carbon, low alloy steels	65 000 psi and less	-20 to 100	Average for 3 specimens	13	10	------
			Minimum for 1 specimen	10	7	
Carbon, low alloy steels	Over 65 000 to 75 000 psi inclusive	-20 to 100	Average for 3 specimens	15	13	------
			Minimum for 1 specimen	12	10	
Carbon, low alloy steels	Over 75 000 to but not including 100 000 psi	-20 to 100	Average for 3 specimens	15	13	------
			Minimum for 1 specimen	12	10	
Carbon, low alloy steels	100 000 psi and over	-20 to 100	Minimum for 3 specimens	---	---	0.015 (15)
Types 304, 304L, 347 stainless	------	below -325		---	---	
FeM (chromium) stainless	------	below -20		---	---	
FeA (chromium-nickel) stainless with carbon greater than 0.10 percent	------	below -20		---	---	
FeA stainless with alloy content in excess of AISI limits	------	below -20		---	---	
High alloy steels in castings	------	below -20		---	---	
Types 309, 310, 316, 309Cb, 310Cb, or 316Cb stainless	------	All temperatures		---	---	

[a]From information in ref. 11.

temperature (NDT), the metallurgical structure of the steel changes with a resulting change from ductile to brittle behavior. Metallurgical influences on the NDT will be discussed later. The presence of the notch constrains the material in a triaxial state of tensile stress at the root of the notch which reduces plastic behavior: tensile strains in the longitudinal direction cannot be made up for by necking-in deformations in the transverse directions (ref. 9, pp. 81 to 85).

The most widely recognized test to measure the brittle nature of metals is the notched bar impact test (ASTM E23-66, ref. 10, pp. 275 to 289). Therein, the energy necessary to fracture a notched specimen and the bulge or lateral expansion at the fracture site are measured. The impact energy level that the particular metal must survive is a function of the end use. The ASME Pressure Vessel Code (ref. 11) recognizes the following (table IV) minimum acceptable impact energy conditions for steels for pressure vessel construction at the temperature and condition for which service is intended. Paragraph UG-84 of Division 1 and Article M-2 of Division 2 of Section VIII of the ASME Boiler and Pressure Vessel Code must be consulted when defining the impact test requirements for steels for pressure vessel applications.

The specimen configurations for the Charpy tests are shown in figure 3. A more complete description of specimen types is given in reference 10 (pp. 282 and 287).
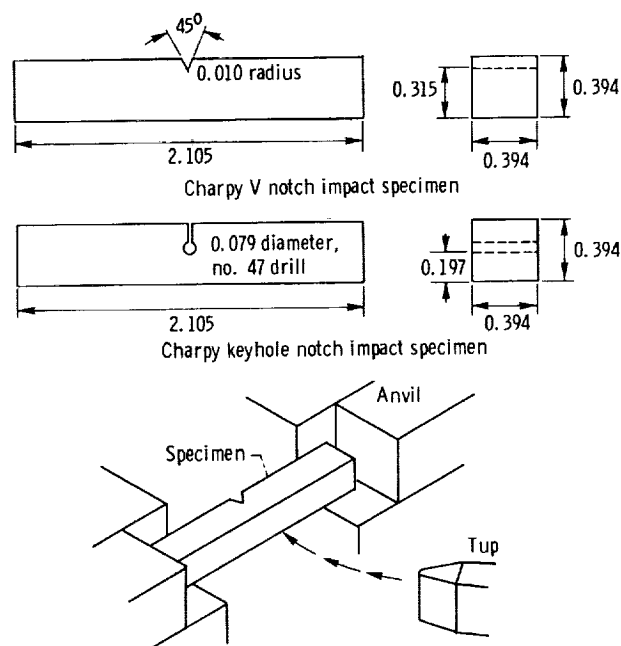

Figure 3. - Charpy test specimens and test method (ref. 8, p. 159). All dimensions are in inches.

Three things must be recognized when reviewing data on impact strength:

(1) The results are functions of the specimen configuration such that Charpy keyhole, Charpy V-notch, Izod specimen, etc. tests will not correlate.

(2) The impact test provides quantitative comparisons on a selected specimen, but data cannot be converted into energy values that would serve for engineering design calculations.

(3) Impact strength is a criteria that must be applied regardless of the type of oxygen service, whether it be a stainless steel for the containment of LOX or a carbon steel for gaseous oxygen service at room temperature (ref. 10, p. 287).

An excellent discussion on the transition between ductile-to-brittle behavior as evidenced by impact testing is given in reference 8 (pp. 18 to 27).

Effect of steel plate thickness. - In general, the NDT temperature increases as the rolled plate thickness increases (fig. 4). This is principally due to a lack of grain refinement as one progresses into the center of a thick rolled section. The transition temperature should be determined from specimens of full plate thickness if the standard range of Charpy specimen widths can accommodate this restriction (see ref. 10, pp. 275 to 289).
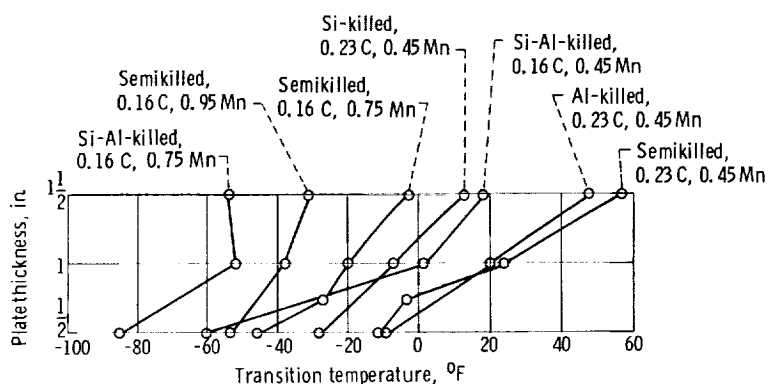
Figure 4. - Average curves showing effect of plate thickness on keyhole Charpy ductility transition temperatures of various carbon steels (ref. 8, p. 30).

Effect of specimen orientation. - In general, specimens oriented parallel to the rolling direction and notches parallel to the plate surface give higher impact energy values than specimens oriented transverse to the rolling direction and notches normal to the plate surface (fig. 5). The usual procedure is to use the LH specimen orientation shown in the figure.
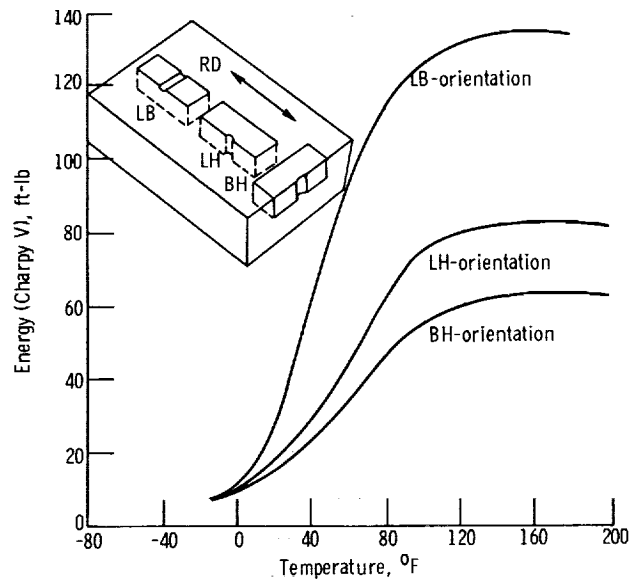
Figure 5. - Effect of Charpy V transition curves of notch and specimen orientation relative to rolling direction (ref. 8, p. 66).

Effect of metallurgical factors. - Increases in carbon content tend to increase the transition temperature and to reduce the abrupt transition from ductile to brittle behavior (fig. 6). This is true for all types of steels including stainless steels. As the temperature is lowered and the change from austenite to martensite begins, the carbon is precipitated out of the crystalline structure. This causes a bonding action which prevents the metal from slipping in shear (the criteria for ductile behavior) causing the failure to occur in cleavage (the criteria for brittle behavior) (ref. 12, pp. 144 and 145).
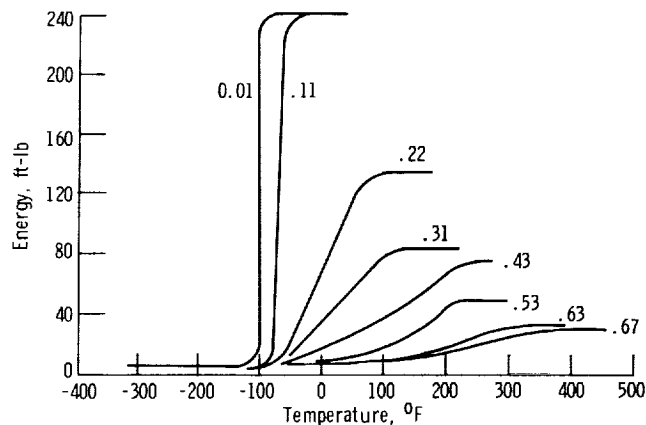
Figure 6. - Effect of carbon on shape of Charpy V transition curve (ref. 8, p. 36).

12

Increases in nickel content tend to decrease the transition temperature and to reduce the abrupt transition between ductile and brittle behavior (fig. 7). At high (>42 percent) nickel content, the austenite phase is completely stabilized such that no brittle transformation is possible (ref. 12, p. 58).
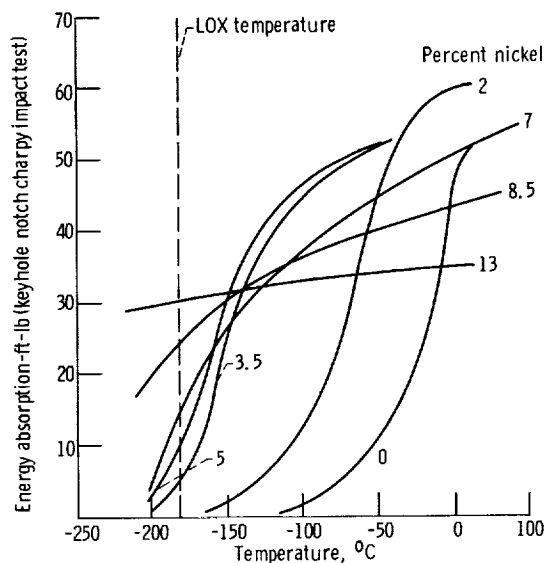
Figure 7. - Effect of nickel on impact properties of steel
(ref. 13, p. 48). Source, International Nickel Company.

Table V lists the constituents that are commonly found or added during the manufacture of carbon or low alloy steel that have a significant effect on impact strength.

TABLE V. - EFFECT OF ALLOY CONSTITUENT ON IMPACT

STRENGTH OF LOW ALLOY STEELS[a]

Alloy	
Manganese	Lowers NDT temperature 0.75° to 1° F for every 0.01 percent increase in manganese up to 1.5 percent
Silicon	Present in killed steels in amounts of 0.15 to 0.30 percent; silicon seems to lower NDT temperature
Phosphorus	Drastically raises NDT temperature, about 7° to 13° F for each 0.01 percent of phosphorus
Nitrogen	Moderately raises NDT temperature; most evident in strained and aged material
Aluminum	Lowers NDT temperature in silicon-killed steels, especially in thick plates where problem is more critical

[a]From information in ref. 8, pp. 36 to 39.

13

Specifically, the manganese-to-carbon ratio is of most important note in the selection of pressure vessel steels. The Mn/C ratios greater than 2.5 provide a steel for use down to about -20° F; Mn/C greater than 4.5 are used down to -70° F; and fine grained manganese, low carbon steels treated with aluminum, niobium, or vanadium for extra grain refinement can be used down to -130° F.

Steels with finer grain size, other things being equal, have lower transition temperatures than coarser grained steels. Doubling the number of grains lowers the Charpy keyhole NDT temperature on the order of 20° to 30° F (ref. 8, pp. 36 and 37).

The relevance of steelmaking methods on the notch impact strength is presented in tables VI and VII.

TABLE VI. - STEELMAKING PRACTICE[a]

Method	Production quantity, percent	Characteristic product
Open hearth	87	0.025 to 0.03 percent sulfur, less than 0.006 percent nitrogen results in good impact toughness
Acid Bessimer	3	0.015 Percent nitrogen; 0.7 to 0.12 percent phosphorus results in compromised impact toughness; tube and pipe frequently fabricated from acid Bessimer stock
Electric furnace	10	Similar to open hearth except slightly higher nitrogen; therefore, slightly lower impact toughness

[a]From information in ref. 8, pp. 33 to 35.

TABLE VII. - DEOXIDATION PRACTICE[a]

Method	Characteristic product
Rimmed steel	Strong evolution of carbon monoxide takes place during freezing of ingot resulting in variable carbon content; low Mn/C ratio, relatively high oxygen, nitrogen content results in poor impact toughness
Killed steel	Silicon and/or aluminum added to completely stop carbon/oxygen reaction resulting in superior impact toughness; expensive
Semi-killed steel	Lie between rimmed and killed steels in practice and resultant impact toughness

[a]From information in ref. 8, pp. 33 to 35.

Characteristics of Various Stainless Alloys

Reference 6 divides stainless steels into two basic types - austenitic (FeA) and martensitic (FeM). In addition, two other groups of steels, age hardening (FeAH) and nickel steels, are closely allied to stainless steels and will be discussed here. The FeA steels are the most widely used stainless steels in oxygen systems (ref. 13, pp. 39 to 42). These steels are annealed by quenching from the austenitic temperature range. Strength is improved from the annealed condition only by cold working. The FeA stainless steels with less than 18 percent nickel will partially revert to martensite when exposed to LOX temperatures, especially when the material is strained (forced to change shape) at LOX temperatures. Carbon and nitrogen tend to stabilize (prevent) this transition, but the resulting metallurgical structure will be more brittle due to the formation of compounds at the grain boundaries containing residual carbon and nitrogen. The preference (from a toughness standpoint) is to allow or sometimes encourage the formation of some martensite but not to allow sufficient carbon and nitrogen to be present to precipitate as a result of this transformation. The low carbon (designated by the suffix L) versions of the FeA steels are therefore favored for cryogenic LOX applications. Due to the many variables involved in the amount and properties of the martensite formed the subject can only be discussed qualitatively, such as is done in table VIII.

TABLE VIII. - MARTENSITE TRANSFORMATION IN AUSTENITIC STAINLESS STEEL[a]

Factor	Amount	Type of stainless steel	Amount of martensite formed at LOX temperature	Nature of martensite formed	Prevailing threat or advantage
Nickel content	Low	201	Much	Could be brittle	Low toughness, dimensional change
	Medium	304	Some	Most likely ductile	Dimensional change
	High	310	None	----------------	No toughness change, no dimensional change
Carbon, nitrogen content	Low	304L	Much	Tough	Acceptable toughness, dimensional change
	High	304	Some	Very brittle	Possible[b] brittle behavior
Low (LOX) temperature straining	Mild	----	Some	Tough	Acceptable toughness
	Severe	----	Much	Tough	Possible[b] brittle behavior
Room temperature straining before LOX use	Mild	----	None	----------------	None
	Severe	----	Some	Tough	Minimizes brittle behavior of low nickel or high carbon alloys

[a]From information in ref. 12, pp. 57 to 65.
[b]When combined with other bad factors.

Some of the FeA stainless steels (most notably type 304) exhibit yield strengths that are only one-third to one-quarter of the tensile strength. To prevent permanent structural deformations, the designer must base the working stress below the yield strength. The strength to weight ratio of these FeA stainless steels is therefore compromised over the other types to be discussed. The FeM stainless steels can be quenched from the temperature at which austenite exists (1700° to 1900° F) and tempered between 400° and 1400° F to develop high (180 000 to 200 000 psi) tensile strength. These steels contain little or no nickel and 11.5 to 18 percent chromium and can be welded or cast. The most commonly used types are 410 (12Cr, low carbon) and 430 (16Cr, low carbon). While these steels are acceptable for use in gaseous oxygen systems at room temperature, the inherent martensitic structure is brittle at LOX temperatures prohibiting them from use in pressure vessel applications with LOX but making them ideal for applications (including LOX) requiring hardness and wear resistance. Carbon is added to FeM stainless steels to further enhance the characteristic of high hardness. The prime example, type 440C, is commonly used in bearings in LOX systems.

Age hardening (FeAH) stainless steels derive their strength from complex (often proprietary) combinations of strain and age hardening. Tensile strengths up to 240 000 psi can be obtained. Because of the nickel content of these steels, fire compatibility with gaseous oxygen is as good as FeA stainless steels, permitting their use therewith. However, as with FeM stainless steels, FeAH steels generally become notch sensitive at liquid oxygen temperatures, similarly curtailing their use.

Nickel steels are commonly used in LOX systems (where large amounts of material are required) to avoid the high cost of FeA stainless steels. A minimum of 9 percent nickel (ASTM-A353) is required to keep the notch toughness acceptably high at LOX temperatures. Even so, the notch toughness of 9 percent nickel steel is reduced to 50 percent of the toughness of FeA type 304 at LOX temperatures, suggesting a smaller critical flaw size for 9 percent nickel steel. ASME allowable stresses for this material (22 500 psi, 1/4 of the yield) should therefore be respected. For applications where the ASME pressure vessel code does not apply and stresses closer to yield are necessary, 9 percent nickel steels should not be used in favor of materials with a greater notch toughness ratio at liquid oxygen temperatures. Nine percent nickel steel is not corrosion resistant. Oxide scales will form in the presence of moist or saline air. Scales of this sort can be carried as reactants by fluid flow through the system. It is therefore necessary to establish relatively tight controls on moisture and other atmospheric contaminants from the inside of 9 percent nickel oxygen vessels, even during periods of nonuse.

Types of and Specifications for Stainless Steel Alloys for Oxygen Service

Tables A-I and A-II in the appendix (ref. 6, secs. 13XX to 16XX) list the applicable specifications and special considerations governing the use of stainless steels.

ALUMINUM AND ALUMINUM ALLOYS

Aluminum and its alloys require a relatively large amount of energy to react with oxygen and are therefore considered acceptable, with basic precautions, for structural use in oxygen systems. Aluminum alloys derive their resistance to reaction in oxygen by the natural formation of a thin protective oxide surface film that protects the substrate from further oxidation. High (7500 psi) pressure of oxygen does not effect this film, but temperatures in excess of 1200° F cause a loss of film coherence. A situation such as this is not inconceivable, since a rapid surface reaction could produce a molton zone at this temperature while the rest of the structure remained structurally intact at ambient temperature. Above 1200° F it becomes possible to burn the metal (ref. 3, p. 12). For rapid combustion to proceed, the temperature must exceed the melting point of aluminum oxide (3700° F). Sudden disruption of the film at lower temperatures such as by mechanical or chemical means permits ignition, and under these conditions the ignition point also becomes influenced by oxygen pressure. The quantitative levels of energy rate causing ignition of aluminum at various temperatures and pressures are not known, so the process of designing aluminum into an oxygen system in a fire-safe manner consists of rigidly adhering to criteria developed from use experience.

Applications and Limitations in Oxygen Systems

Aluminum and aluminum alloys are found in all phases of oxygen manufacture and use. Table IX summarizes the advantages and disadvantages of each major application.

In ground liquid oxygen systems, aluminum is used extensively for tankage, lines, pump and valve components, and heat exchangers (ref. 14, pp. 305 to 310). Aluminum is the lowest cost material suitable for use with liquid oxygen and directly competes with 9 percent nickel steel in this application.

In aerospace liquid oxygen systems, aluminum frequently becomes the primary structural material by virtue of its light weight. Figure 8 shows the application of aluminum alloys to the Saturn V, S-1C stage. The critical failure mode of such a structure is buckling; therefore, the added wall thickness permitted within the weight allowance by the low density of aluminum is beneficial (ref. 14, p. 441). However, very special

TABLE IX. - FACTORS AFFECTING USE OF ALUMINUM IN OXYGEN SYSTEMS

Application	Favorable factor	Unfavorable factor
General O_2 use	High amount of energy required to ignite aluminum (ref. 14, p. 922)	Combustion characterized as violent (ref. 4, p. 8)
Liquid oxygen (LOX)	No brittle phase transformation at cryogenic temperatures; low cost	Coefficient of thermal expansion higher than other acceptable materials (ref. 13, p. 75)
Ground LOX systems	Light weight improves payload efficiency of ground transport (ref. 14, p. 309)	High heat extraction of aluminum increases boiloff losses (ref. 13, pp. 26 and 27)
Aerospace LOX systems	Good strength to weight ratio, ease of fabrication, especially in large construction (ref. 14, pp. 441 to 451)	Surface scales may form (due to atmospheric exposure) perhaps hindering maintenance of cleanliness; certain high-strength alloys difficult to purchase in small quantities
Oxygen heat exchangers	High thermal conductivity provides compact design (ref. 14, pp. 305 and 306)	Must be fabricated by flux-brazing; selection of alloys limited (ref. 14, pp. 305 and 306)
Gaskets	Good conductivity, nil creep or relaxation at LOX temperature	Requires higher compression to seal than nonmetallic gaskets, thermal expansion characteristics usually different from surrounding structure creating possibility of leakage

1 Forward skirt structure, alloy 7075-T6
2 Gox distributor, alloys 2219-T87, T81 and T6
3 Oxidizer tank, alloys 2219-T87, T81 and T6
4 Antislosh baffles, alloys 2024-T3 and 7178-T6
5 Antivortex device
6 Cruciform baffle
7 Intertank structure, alloy 7075-T6
8 Fuel tank, alloys 2219-T87, T81 and T6
9 Suction line tunnels, alloy 2219-T81
10 Oxidizer suction lines
11 Fuel suction lines
12 Center engine support, alloys 7075-T6 and 7079-T6
13 Thrust column, alloy 7075-T6
14 Holddown post, alloy 7079-T6
15 Upper thrust ring, alloy 7075-T6
16 Lower thrust ring, alloy 7075-T6
17 Engine fairing, alloy 7075-T6
18 Fin, alloys 2024-T3 and 7075-T6
19 F-1 engine
20 Retrorockets
21 Gox line
22 Helium line
23 Helium bottles, alloy 2014-T6
24 Helium distributor
25 Oxidizer vent line
26 Instrumentation panels
27 Cable tunnel
28 Umbilical panel
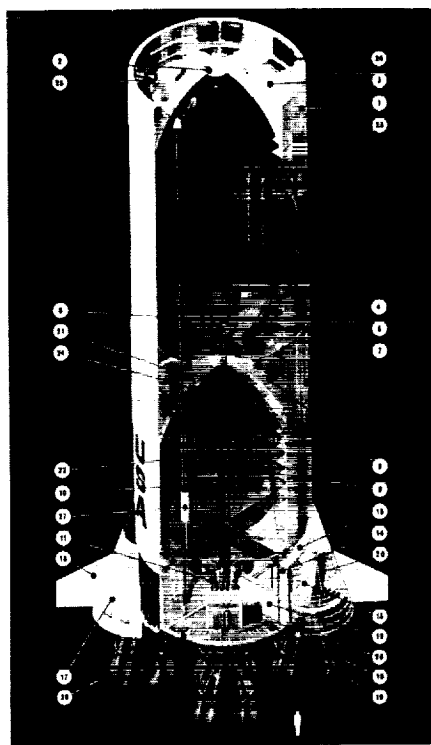
Figure 8. - Use of aluminum on S-1C stage (ref. 14, pp. 442 and 443).

treatment of aluminum is necessary in aerospace applications, especially with the 7XXX series alloys. Most of these aluminum parts are given detailed stress analysis and most are subsequently painted on exterior surfaces after assembly to counter the high susceptibility to stress corrosion when high stresses are present.

In room temperature oxygen systems, the role of aluminum is generally relegated to small component construction, because carbon or alloy steels have the advantage of either lower cost or lighter weight by virtue of their high strength. These steels cannot be used at cryogenic temperatures because of brittle phase transformation.

In elevated temperature oxygen systems, aluminum is not used because its strength deteriorates rapidly above 400° F (ref. 5, pp. 878 and 879).

In high pressure oxygen systems, the relatively low strength of aluminum necessitates a greater wall thickness, favoring the use of high strength nickel or iron base al-
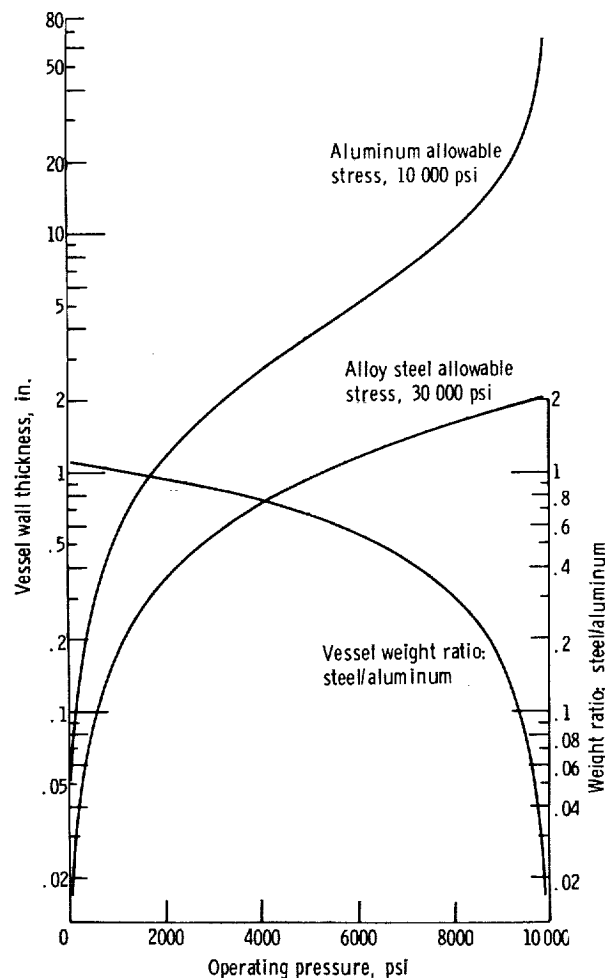
Figure 9. - Aluminum against steel for high pressure
gaseous oxygen containment in a 10-inch inside
diameter cylindrical vessel.

loys. This is exemplified in figure 9, based on ASME Pressure Vessel Code Requirements (ref. 11).

In situations where no practical recourse exists to avoid injury or loss of life in the event of fire, aluminum is not used because of the observed violence of combustion in concentrated oxygen (ref. 4, p. 8). Alloys of nickel or copper are somewhat more difficult to ignite, and they burn much less violently than aluminum (ref. 4, pp. 32 to 34 and ref. 15, pp. 917 to 923).

Aluminum Alloys Suitable for Oxygen Use

Subject to the factors herein, all alloys of aluminum defined by processing factors given in reference 16 and by specifications as shown in table A-III (ref. 17, pp. 162 to 164) of the appendix can be used in oxygen systems. Descriptions and attributes of various aluminum alloy series are contained in table X.

Processing and Fabrication Factors

Strengthening and temper designation. - Aluminum alloys are strengthened by strain hardening and/or heat treatment. All alloys are annealed, called the "O" condition, by heating to a temperature between 650° and 800° F followed by a slow (50° F/hr) furnace-controlled cooling procedure (fig. 10) or a more rapid air-cooling procedure. Alloys 2XXX, 6XXX, 7XXX, and some casting alloys will strengthen with age and temperature. Aging response is made possible by first creating the "W" condition which consists of heating to between 900° and 1000° F followed by a rapid quench to hold constituents in solution. Care must be taken not to overheat the material because local melting or oxide formation will either result in weak spots or brittleness. The delay between extraction of the alloy from the solution bath and quench should be minimized because of possible segregation of constituents, resulting in reduced corrosion resistance (ref. 6, secs. 32XX-33XX). This procedure allows certain of the alloying elements to enter into a solid solution with the aluminum and subsequently to be entrapped in solution during the quench. The alloy is then naturally aged at room temperature or artificially aged at elevated (250° to 400° F) temperatures.

All aluminum alloys are strengthened by straining past the yield point. This can be done during stock processing (tube extrusion, etc.) or finished part processing (die forging, etc.). The properties of the 5XXX (magnesium-containing) alloys should be stabilized by a low temperature heating cycle after strain hardening if properties changes are to be avoided over a long time at room temperature. Alloys 2XXX and 7XXX that are

TABLE X. - DESCRIPTION OF ALUMINUM ALLOYS[a]

Alloy series	Composition	Strengthening methods	Factors affecting use
1XXX	99.0 to 99.6 percent pure aluminum	Cold work only	All 1XXX are readily weldable by all methods. All are very ductile and suitable for deep forming operations. All are more tough at cryogenic temperatures than at room temperature, even after severe cold working. Annealed or partially worked stock is too soft to machine to a high surface finish. High thermal conductivity produced by low alloy content improves fire safety. Low strength curtails high performance applications.
2XXX	93 to 95 percent aluminum, balance principally copper	Cold work plus aging at room or elevated temperature	Weldability and formability decrease with increasing strength. Weldable by gas-tungsten-arc (GTA) or gas-metal-arc (GMA) methods only. Alloy 2219 has excellent weldability, medium strength, good cryogenic toughness, and excellent stress corrosion resistance, allowing its use in LOX and GOX pressure vessel applications. Alloys 2014 and 2024 progressively sacrifice the above for strength improvements. Alloy 2219 can develop weld strength equal to parent metal strength if postweld heat treatment is employed.
3XXX	98 to 99 percent aluminum, balance manganese	Cold work only	Strength slightly higher than 1XXX but considerably lower than other aluminum alloys. All have excellent cryogenic toughness. Alloy 3003 is readily brazed and has high thermal conductivity and for this reason is used extensively in heat exchangers.
5XXX	94 to 96 percent aluminum, balance principally magnesium	Cold work only	Readily welded by GTA and GMA methods. Welding reanneals the material in the heat affected zone but the as-welded strength is typically higher than other alloys. The 5XXX alloys are the most widely documented and characterized of the aluminum family. All are more tough at LOX temperature than at room temperature. Because of the above, 5XXX alloys, notably 5083 and 5456, are widely used for LOX tankage where postweld heat treatment is avoided because of difficulty or expense.
6XXX	98 to 99 percent aluminum, balance magnesium and silicon	Cold work plus aging at room or elevated temperature	Easily forged, excellent cold formability, weldable by GTA or GMA methods. Welds must be heat treated to approach the strength of 5XXX weldments. Good cryogenic toughness. Used mainly as extrusions, forgings, and small weldments such as pipe, pipe fittings, and valve bodies in LOX service. Alloy 6061 is the most documented and widely used of this group. Alloy 6063 is lower in cost and strength.
7XXX	88 to 93 percent aluminum, balance principally zinc	Cold work plus aging at room or elevated temperature	Highest strength of all aluminum alloys. The copper-free X7005, 7039, and X7106 are weldable by GTA and GMA methods; all others are not weldable. Toughness is generally reduced at cryogenic temperatures. Used in aerospace LOX systems as forged and machined components where high strength is essential and high levels of process control and inspection are possible. Unfavorable for use as LOX pressure vessels because of low toughness.
Casting alloys	----------------	Age hardenable	Casting alloys with low alloy content or with silicon or magnesium silicide are well suited for LOX applications with no loss in toughness. Alloys C355 (5Si, 1.3Cu, 0.5Mg) or A356 (7Si, 0.3Mg) are ideal representations of the above. The conventional forms of these alloys, 355 and 356, contain more impurity and are relegated to conventional casting practice with no guarantee on minimum mechanical properties.

[a]From information in ref. 6, secs. 32XX and 33XX.
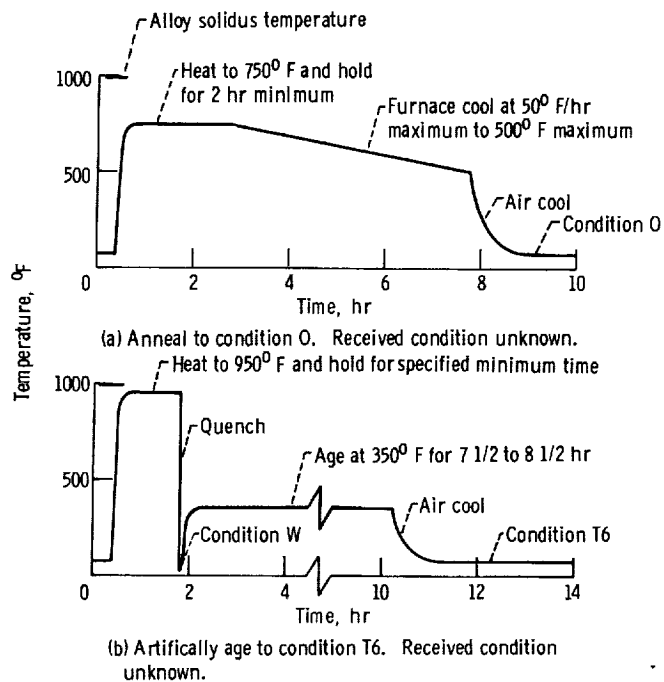
Figure 10. - Typical heat treatments for aluminum alloys.

strain hardened and aged to high strength levels should receive special processes to reduce residual stresses. These processes include (1) application of plastic strain prior to aging (called stretching), (2) initiation of strain hardening as quickly as possible after solution treatment, (3) quench using hot (180° F) water bath or spray, and (4) liquid nitrogen cool after quench followed by a steam spray. These and other special processes serve to reduce high residual stresses by localized yielding while the metal is in a ductile condition (ref. 16, pp. 371 to 381). Removal of high residual stresses reduces the threat of failure by stress corrosion or thermal shock. Tempers of aluminum are designated in accordance with table A-IV (see appendix).

Casting. - Aluminum is cast by all known practices. The selection of casting practice for oxygen system components should be in accordance with the following criteria:

(1) Alloys C355 or A356 should be used unless a particular requirement is not satisfied by this selection. These alloys have been highly characterized and widely used in the aerospace industry. These alloys are recommended because they posses excellent pressure tightness and can be used in a casting process (permanent mold) that produces smooth surface finishes.

(2) Sand and shell mold castings should be avoided in favor of die, investment, or permanent mold castings specifically because of the superior surface finish produced by the latter.

22

(3) Castings used for oxygen containment purposes should each be proof pressure tested with leakage rate included as a condition of acceptance.

(4) Castings should not be applied where high resistance to fatigue through cyclic loading is required.

Forging. - No restriction is placed on the forging practice; however, the designer would do well to design the forging and create controls on the forging process such that flow lines are in the direction of the major applied service load. Alloys 2024 and 7075 should be avoided except where high strength is essential. This is because of the low toughness level of these alloys and their strong properties dependency on temperature. Where 2024 and/or 7075 must be used, fracture mechanics analyses should be employed to determine critical flaw sizes, and 100 percent nondestructive inspection should be used that will detect these flaw sizes. Alloys 2219, 5052, and 5456 are preferred in that order for forging. Alloy 2014 is used extensively for forgings but its resistance to corrosion is compromised because of the residual stresses induced by forging (ref. 6, sec. 3201).

Welding. - Alloys 7075 and 7178 cannot be welded. Alloy 2024 is very difficult to weld. Most other alloys of aluminum are weldable. All internal weld areas in oxygen systems should be dressed smooth and continuous to the parent metal. Weld joints exposed to the inside of the oxygen system should be designed to facilitate dressing and weld surface inspection. Only those weld joint designs should be used that provide for full-thickness weld penetration; crevices between welds and parent surfaces in contact with oxygen due to lack of penetration can trap contamination.

Table XI shows several alloys that can be welded by all conventional processes. It

TABLE XI. - WELDING OF

ALUMINUM ALLOYS[a]

Alloys	Weld filler
A356	4043
1060	1260
1100	1110
2219	2319
5052	5154
5456	5556
6061	4043

[a]From ref. 6, secs. 32XX and 33XX.

is suggested, however, that only GTA (gas tungsten arc), GMA (gas metal arc), or EB (electron beam) processes be used for routine oxygen system welds because (1) the possibility of introducing contaminants by the shielding media is minimized, (2) flux residues are eliminated, and (3) the soundness and surface smoothness of GTA, GMA, and EB welds are generally superior. The GMA and EB welds eliminate the possibility of tungsten inclusions. Weld soundness is better with EB and GTA processes. The EB welds may produce a sharp radius crown that requires machining off to produce smooth surface continuity. Hydrocarbons and water soluble lubricants must be controlled on the weld surfaces and the weld filler material as these contaminants are capable of destroying the favorable mechanical properties of the joint. When a weld overpass is delayed for a period of time, the cleanliness of the general weld area must be maintained. In an oily shop atmosphere this problem may require special controls. Those alloys exhibiting the highest weldability are 5456, 5052, 5083, 1100, 6061, and 2219, followed by C355, A356, 2014, and 2014 (ref. 6, secs. 31XX to 33XX).

Surface treatments. - The use of anodic films and passivation techniques offer no advantage on aluminum surfaces in contact with oxygen and are therefore not recommended. These surface treatments may, in fact, produce an undesirable effect such as rough surfaces or the introduction of less desirable metal oxides in the surface film. A bright, shiny, smooth aluminum surface, protected within its own film, is the superior surface. Surface treatments on exterior surfaces, however, are required where corrosive atmospheres are encountered and/or where the alloy of aluminum is relatively sensitive to the effects of corrosion. Zinc chromate primers are impact sensitive with oxygen and are therefore prohibited on surfaces in contact with oxygen. Because of the possibility of spray contamination, exterior surface protection consisting of zinc chromate is also prohibited in favor of anodic coatings (ref. 18, p. 71).

Design and Use Factors

Thermal conductivity. - Thermal conductivity of metals and alloys is viewed with only casual interest in most structural design applications. However, thermal conductivity in a structure in an oxygen system becomes a direct measure of the resistance of the structure to fire. The structure ignites because sudden energy from some source is momentarily supplied to the surface raising it to the ignition temperature. High thermal conductivity will lower the surface temperature and will therefore increase the resistance to ignition.

The thermal conductivity of aluminum alloys in particular can vary significantly depending on certain processing and compositional variables as shown herein. It is therefore important to use these variables to produce high thermal conductivity as well as meeting other design considerations.

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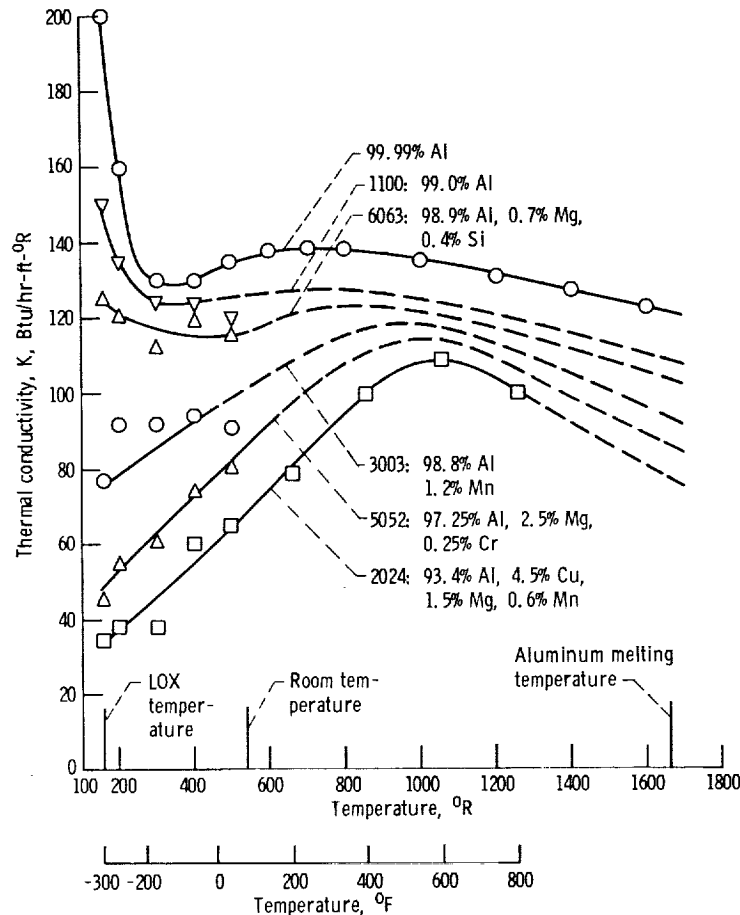
Figure 11. - Comparison of thermal conductivity of several aluminum alloys.
(From information in refs. 19, 20, and 21 (pp. 5 to 32).)

Aluminum alloy thermal conductivity decreases with increasing alloy content espe-
cially at cryogenic temperatures. This is illustrated in figure 11. The most dramatic
change takes place when small amounts of alloy are introduced into pure aluminum. The
change becomes very small when the alloy content increases above 7 or 8 percent (see
fig. 12). Because of this, the designer should favor the 1XXX or low alloy content 6XXX
aluminum alloys where possible.

Aluminum alloy thermal conductivity decreases as the alloy strength level is raised
(see fig. 13). The logical reason for this is that the two strengthening mechanisms, cold
work and precipitation hardening, either increase the number of grain boundaries (grain
refinement) or add to the thickness of the grain boundary, both acting as barriers to the
flow of heat. Because of this, the designer should specify that the alloy be strengthened
no higher than the requirements of the application.

It is important to note that thermal conductivity does not alone determine the rate of

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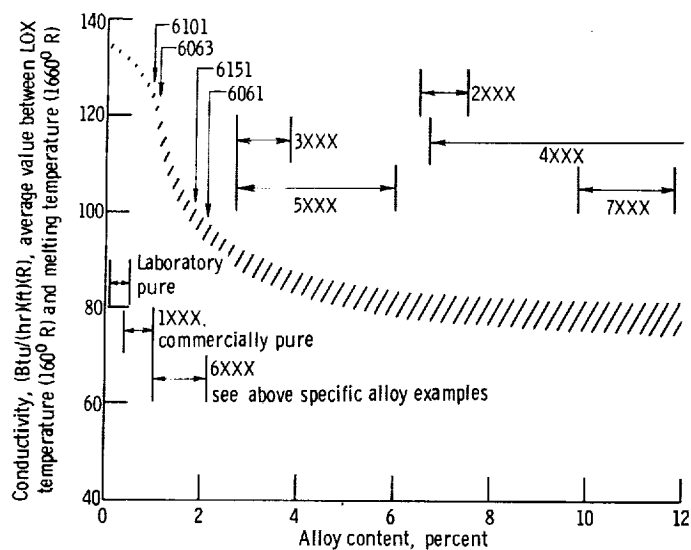
Figure 12. - Thermal conductivity against amount of total alloy constituant for aluminum alloys (cold worked + aged). (From information in ref. 22, pp. 12 to 27.)
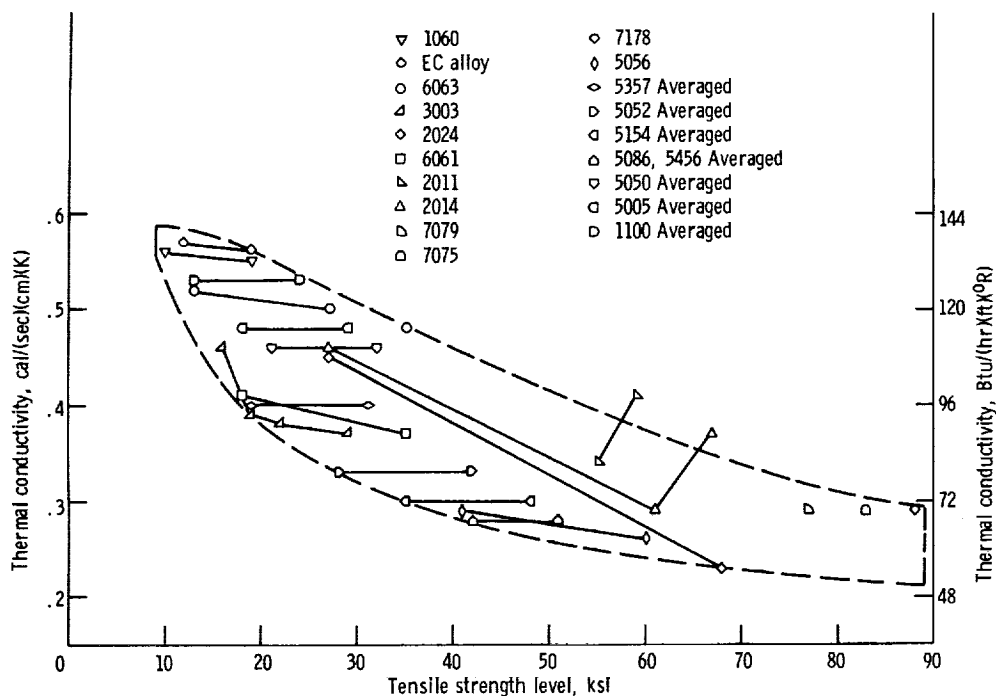
Figure 13. - Effect of strength on room temperature thermal conductivity. Alloys of aluminum strengthened by cold work and/or aging. (From information in ref. 5, pp. 935 to 958; ref. 6, sections 13XX to 16XX; and ref. 23, vol. I, pp. 42, 43, 75, 96, 97, 176, 204, 227, 238, and 246.)

heat transfer into the metal from a surface reaction. It also depends on the metal specific heat and density. These properties, however, are not highly dependent on the alloy content or the strength level. A discussion of the combined effect of conductivity, specific heat, and density is presented in the concluding section of this report.

Metallurgical factors. - Pure aluminum has been shown not to ignite in oxygen until temperatures of 800° to 1000° C, far in excess of its melting point, are reached. Both the melting temperature and the ignition temperature will change as alloying elements are added. Noneutectic alloys that are heated through the melting range will undergo a "slush" phase wherein both liquid and solid exist simultaneously. The chemical composition of the liquid and solid may vary markedly from the composition of the base alloy (ref. 9, pp. 101 to 107). Consider the following phase diagram (fig. 14). A metal of
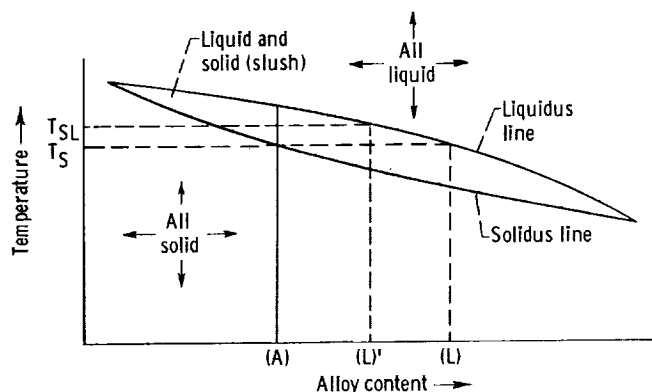
Figure 14. - Illustration of phase relations and compositions at various temperatures.

alloy content (A) is heated to the solidus temperature T_S and a minute amount of liquid is formed. The alloy content of this liquid is not (A) but is (L). Further heating of the metal to T_{SL} produces more liquid but it is now of composition (L)' (ref. 9, pp. 101 to 107). It is important to recognize that should melting of an aluminum alloy take place in an oxygen system, the first liquid to appear will be of substantially different chemical composition and therefore the ignition temperature of this first liquid may be distinctly different from the base aluminum alloy. Ignition of the first liquid will be a sufficient impetus to promote combustion of the remainder of the alloy. The presence of magnesium, for instance, in aluminum in amounts in excess of 20 or 30 percent tends to grossly lower the ignition temperature (fig. 15). The first liquid formed from alloy 5456 (5 percent Mg) will contain approximately 20 percent magnesium (fig. 16). It must be presumed that the resistance of an aluminum - 20 percent magnesium alloy to fire will be somewhat less than pure aluminum. Conversely, the first liquid obtained from aluminum-copper alloys will be enriched in copper (fig. 17) and since copper is very

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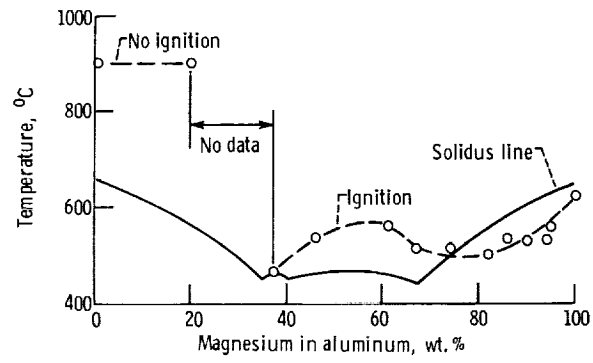
Figure 15. - Solidus line and ignition temperatures for aluminum-magnesium alloys. (From information in ref. 3, pp. A1 and A2.)
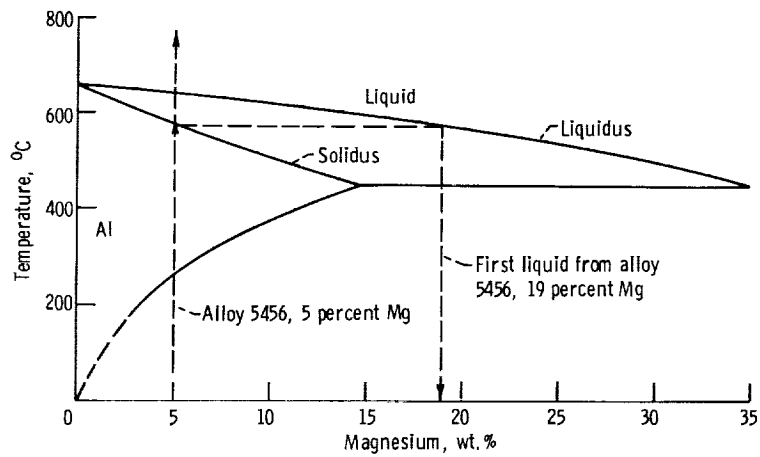
Figure 16. - Phase diagram of aluminum-magnesium system.
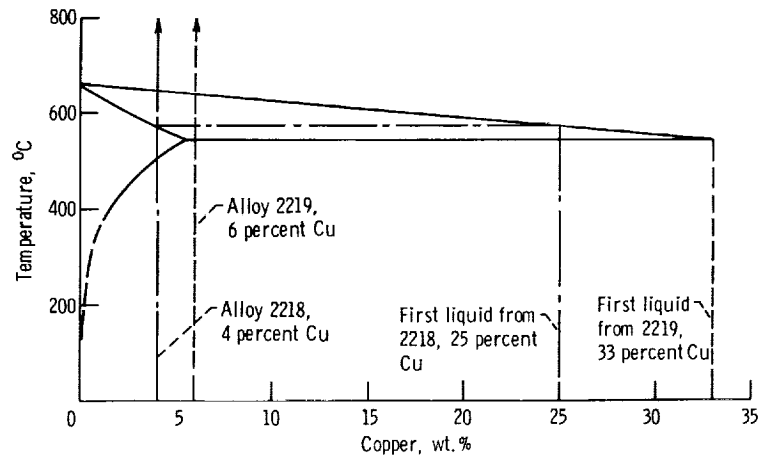
Figure 17. - Phase diagram aluminum-copper system.

28

reluctant to ignite in oxygen it is presumed that a copper enriched liquid alloy will be more resistant to fire than pure aluminum. More aluminum alloy phase diagrams are found in reference 24 (pp. 368 to 396).

NICKEL AND NICKEL ALLOYS

Nickel and nickel alloys form a group of metals that are, together with copper, the most resistant to ignition and combustion in oxygen except for the precious metals platinum, gold, and silver. Nickel alloys can be developed to high strengths with no significant impairment in low-temperature toughness whereas copper cannot. Nickel is characterized by its low heat of combustion and high thermal conductivity in its pure form such that combustion is self-terminating even at high (8000 psi) pure oxygen pressure (ref. 4, pp. 32 to 34). Alloying elements raise the heat of combustion (except copper) and substantially lower the thermal conductivity such that steady but slow combustion is possible. The oxide film that forms on nickel is thin but extremely protective against further oxidation, and the surface remains bright and shiny, even in relatively corrosive environments. High temperature, however, will cause the film to break down resulting in further oxidation. This effects the life of high-temperature components. Inspection for and maintenance of high levels of surface cleanliness is facilitated by this bright surface. The addition of alloying elements (typically Cu, Cr, or Mo) with nickel generally tends to depress the ignition temperature to 100° to 200° C below the melting temperature. However, these alloying elements also greatly improve the strength, hardness, and creep resistance of the metal, with tensile strengths of the order of 90 to 100 ksi. Small quantities of titanium and/or aluminum are added to each of the previous types of alloys to render them precipitation hardening to tensile strengths of 150 to 200 ksi.

Applications in Oxygen Systems - Code Restrictions

Most of the nickel alloys were originally developed for applications requiring strength and oxidation resistance at high temperatures such as jet engine internal components; their use in oxygen systems is a spin-off of the original intent of these developments. Nickel and its alloys are now used extensively in aerospace oxygen systems where extreme (-300° to 2000° F) temperature changes are regularly encountered such as rocket combustion chambers, injectors, and manifolding. Because of high strength and fire resistance, the age hardenable nickel alloys are used for lines and tanks in supercritical oxygen systems.

The high cost of nickel-base alloys generally precludes their use on ground equipment except in small amounts. Invar, the exception, is used in short tubular lengths as fire breaks in long oxygen transfer lines. Invar has the unique characteristic of almost zero thermal expansion (ref. 5, pp. 816 to 819) and is therefore used in situations where temperature-induced dimensional change cannot be tolerated.

Nickel or nickel alloys generally do not undergo a brittle phase transformation in the liquid oxygen temperature environment (ref. 12, p. 56); therefore, they are well suited for pressure-containment applications in such cases. As temperatures are lowered to cryogenic values, the smooth strength and notch strength actually improve while the impact strength remains constant or goes down just slightly. Certain alloys, namely Hastelloy X and those containing cobalt, loose impact strength at cryogenic temperatures and are therefore not well suited for LOX pressure containment applications.

Oxygen systems that are required to meet the ASME Boiler and Pressure Vessel Code (ref. 11, pp. 144 to 149) are constrained in the selection of nickel alloys to those listed in table XII. None of these alloys are precipitation hardenable and must be oper-

TABLE XII. - NICKEL ALLOYS RECOGNIZED BY

ASME BOILER AND PRESSURE VESSEL CODE

Alloy	Composition	Specified minimum tensile strength, ksi
Nickel	99 percent minimum Ni	50 to 55
Monel 400	70Ni, 30Cu	70 to 75
Inconel 600	78Ni, 15Cr, 7Fe	80 to 85
Incoloy	32Ni, 21Cr, 47Fe	65 to 75
Ni-O-Nel	42Ni, 22Cr, 36Fe	85

ated at stresses less than one quarter of ultimate. In applications outside the province of the ASME Pressure Vessel Code, precipitation hardenable alloys may readily be used provided proof testing combined with nondestructive inspection techniques are implemented. As with any high strength material, precipitation hardenable nickel alloys are less tolerant to flaws than lower strength versions. Critical flaw size calculations using fracture mechanics techniques should be made to confirm the suitability of the nondestructive test techniques to be used.

Nickel Alloys Suitable for Oxygen Use

All currently developed and commercially available nickel alloys are suitable for use in oxygen systems except where purchase specifications do not exist. References 5 (pp. 1118 to 1130) and 6 (secs. 41XX and 42XX) list those alloys and applicable specifications. A list of alloys with characteristics representative of the entire spectrum is given in table XIII.

TABLE XIII. - DESCRIPTION OF NICKEL ALLOYS[a]

Alloy	Composition, percent	Strengthening methods	Factors affecting use
Nickel	99.4 Ni	Cold work	Outstanding resistance to fire; characterized as self-extinguishing in pure oxygen to 8000 psi total pressure (ref. 4, pp. 32 and 33). High thermal conductivity. Remains ductile at LOX temperature due to retention of face-centered-cubic (FCC) crystalline structure. Relatively low strength (<40 ksi) compared to other nickel alloys.
Monel 400	70Ni, 30Cu	Cold work	Outstanding resistance to fire. Fabricated by all conventional methods. Develops 140 ksi tensile strength in fully cold worked condition. Ductile at LOX temperatures.
Monel K500	67Ni, 30Cu, 3Al	Cold work plus age hardening	Same as Monel 400 except aging due to aluminum content produces strengths approaching 200 ksi. High strength causes a small but acceptable loss in ductility at LOX temperature and produces a small properties dependency on direction of cold reduction.
Inconel 600	78Ni, 15Cr, 7Fe	Cold work	Fire resistance slightly reduced, conductivity lower, otherwise similar in properties to Monel 400. Available in a wide range of wrought shapes.
Inconel 718	54Ni, 19Cr, 17Fe, 5Cb, 3Mo 1Ti, 1Al	Cold work plus age hardening	Used as manifolds, lines, bellows, injector plates in LOX chemical rocket systems. High (>200 ksi) strength in the aged condition is typical while retention of toughness at LOX temperatures is acceptably high. Aging response is sluggish permitting welding and high temperature forming without leaving high residual stresses.
Inconel X750	73Ni, 15Cr, 7Fe 3Ti, 1Cb, 1Al	Cold work plus age hardening	Similar to Inconel 718. Also used in supercritical oxygen service (tubing, valve bodies) in space life-support systems. Welded only in annealed condition except where service temperatures below 1000° F exist.
Hastelloy C	58Ni, 16Cr, 16Mo, 5Fe, 4W	Cold work plus age hardening	Lower strength and higher density than other age-hardenable nickel-base alloys. Used where sliding contact exists because of its good wear resistance.
Hastelloy X	48Ni, 22Cr, 18Fe, 9Mo, 2Co, 1W	Cold work	Excellent resistance to oxidation at high temperatures. Becomes decidedly brittle at LOX temperatures (impact strength, 20 ft-lb) curtailing its use in pressure vessel applications. High hardness and wear resistance allows use where sliding exists.
Invar	31 to 53Ni, Balance Fe	Cold work plus quench and temper	Used as fire breaks in oxygen lines. Very low coefficient of thermal expansion which can actually be altered to zero or negative values by controls on chemistry and processes. Used where dimensional change due to temperature change must be minimized.

[a]From information in ref. 6, secs. 41XX and 42XX.

Fabrication

A distinct attribute of nickel alloys (especially the nonage hardenable alloys Inconel 600 and Monel 400) is that they are readily fabricated using all conventional industrial techniques for casting, forging, welding, brazing soft soldering, and machining. These techniques are applied with reduced threats that are attendant to certain other metal alloys such as stress corrosion, hot cracking, and carbide precipitation (high temperature sensitization). Heat treatment of age or precipitation-hardenable nickel alloys follows the same general procedure as with aluminum alloys. Over-heating during solution treatment will weaken or detract from the corrosion resistance of the finished product. Special considerations for particular alloys are listed in table A-V (see appendix).

Plating. - Nickel is easily plated on other metal substrates, a practice that can be used to improve the fire resistance of less-compatible metal surfaces. Electrolysis plating techniques provide the least porosity and access of oxygen to the base metal and are therefore recommended. Nickel plating cannot be used to permit an otherwise unacceptable substrate metal in an oxygen system. A complete discussion on nickel plating is contained in references 5 (p. 1114) and 25 (pp. 56 to 61).

Lubrication. - Nickel alloys, especially Hastelloy, are very resistant to sliding wear, galling, and seizure. This property makes them ideally suited for items such as valve stems, screw leads, shafts, bolts, and nuts. Lubricant should be avoided except
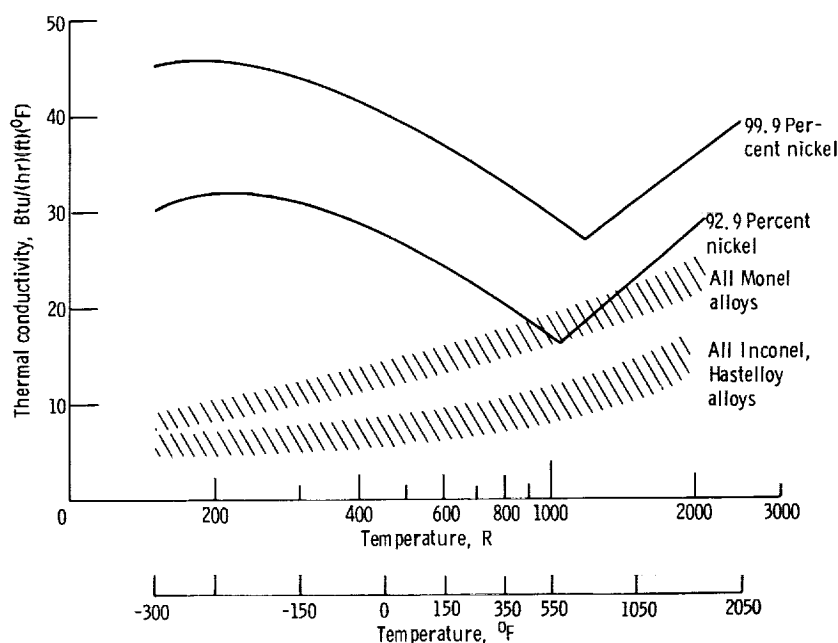
Figure 18. - Thermal conductivity of nickel and nickel alloys. (From information in ref. 5, sections 41XX and 42XX; ref. 23, vol. II, pp. 13, 14, 25, 41, 55, 81, and 144.)

32

where it has been shown by use to be necessary. Fully fluorinated lubricants subjected to batch testing per a specification such as MSFC-SPEC-106B should be used. Holes may be threaded directly into nickel alloys without the need for inserts.

Thermal Conductivity

The thermal conductivity of nickel is lowered by the addition of alloying elements but, unlike aluminum, the amount of cold work or heat treatment has only a small effect. Addition of copper (Monel) does not lower the thermal conductivity as much as addition of chromium or iron (Inconel, Hastelloy) (see fig. 18). Pure nickel should be favored over nickel alloys except where strength or hardness considerations dictate otherwise.

COPPER AND COPPER ALLOYS

Copper and copper alloys provide a highly compatible group of metals for use in both liquid and gaseous oxygen systems. Pure copper must be forced by a massive donor to ignite even in 7500 psi oxygen (ref. 4, pp. 32 to 34). Even then combustion is moderate and, more often than not, self-quenching. The effect of alloying elements on the ignition of copper is not known but it is presumed that ignition temperatures are lowered by virtue of the more reactive species present. Furthermore, the high thermal conductivity of pure copper is significantly lowered by the addition of alloying elements, causing the surface temperature of the alloy to rise more rapidly than that of the pure metal under conditions of identical heating.

Applications in Oxygen Systems

Copper and its alloys exist as a face-centered-cubic crystalline structure from absolute zero to several hundred degrees above room temperature providing for outstanding toughness and notch insensitivity at both liquid and gaseous oxygen temperatures. Copper and copper alloys are used in the fabrication of castings, forgings, gaskets, screw machine parts, and as low pressure tubing in virtually all phases of oxygen manufacture and use. Copper alloy castings have replaced aluminum alloy castings in certain instances, such as LOX centrifugal pump impellers to combat fires initiated by rubbing friction and wear. Further applications are limited for two reasons:

(1) Copper can be readily cold formed only in its unalloyed or annealed state where its strength is limited to 10 000 to 20 000 psi limiting its use in such applications as pressure vessels and high pressure tubing.

(2) Copper is often difficult to weld so the resort is to silver brazing techniques and sleeve joints (potential contaminant traps) or inert-gas furnace brazing techniques which limit the size of the assembly.

Morever, copper alloys are no different from any other cold workable metal in that exposure to the solution temperature such as with brazing, welding, etc., will destroy most of the strength derived from the cold work, resulting in low joint efficiencies (ref. 5, pp. 962 and 963).

Oxygen by itself will not corrode copper, but outdoor exposure will eventually produce a characteristic green patina which could if swept away by the working fluid and become the stimulus for a reaction elsewhere within the oxygen system. It is therefore necessary to seal and protect copper-containing oxygen systems from such exposure much as with 9 percent nickel steel systems.

If mild tool rake angles are used, and the material is cold worked to greater than half-hard, copper alloys are easily machined and can be readily finished to low surface roughness values. Production of a good machine finish on annealed or low strength copper alloys is difficult.

Copper Alloys Suitable for Oxygen Use

Tables A-VI and A-VII (in the appendix) list the properties and applications of copper and copper alloys for use in oxygen systems.

Zinc contents in excess of 30 percent in copper alloys (brass) should be avoided because of the appearance of the relatively brittle beta phase. Brasses are supplied in all cold wrought forms and are commonly used in the manufacture of machined hardware suitable for LOX or GOX service such as tube fittings and parts for valves. The addition of 0.5 to 3 percent lead improves the machinability. Aluminum, tin, silicon, iron, and manganese additions to brass greatly improve the strength as a function of the amount of cold work and enhance the resistance to corrosion. This is important because excessive amounts of cold work in copper alloys will leave high enough residual stresses to cause stress corrosion cracking.

Copper-tin (bronze) alloys are generally cast, some time forged. Aluminum, manganese, silicon, and nickel are additives that increase the tensile strength. Manganese and aluminum bronzes produce high quality castings with tensile strengths of 115 000 psi with 20-percent elongation. Lead in these bronzes should not exceed 0.1 percent because of detrimental effect on toughness and strength. Bronzes are used extensively in oxygen systems where sliding contact is required such as with gears, bushings, and screw leads. Aluminum bronzes have a high fatigue limit, considerably in excess of manganese bronze or any other copper casting alloy.

34

Phosphor bronzes are copper-tin bearing and gear alloys with between 0.01 and 1 percent residual phosphorus which, depending on the amount, imparts high hardness to the surface. As with beryllium copper, however, these alloys are relatively brittle.

Nickel silvers are casting alloys of copper containing 17 to 20 percent zinc and 10 to 25 percent nickel plus lead and tin. Tensile strengths vary with nickel content up to 65 000 psi for the 25 percent nickel alloy. Nickel silvers are marked by exceptional corrosion resistance and notch toughness between cryogenic and room temperatures and (except for strength) approach Monel and Inconel castings in these attributes. Copper-nickel alloys (containing 10 or 30 percent nickel, balance copper) are similar in characteristics to nickel-silvers except for somewhat reduced strength and better resistance to stress corrosion cracking. Copper-nickel alloys require full stress relieving or solution annealing prior to exposure to solders or brazes, otherwise brittle alloy phases will appear due to migration of the filler metal into the base metal.

Restrictions on Heat Treatable Copper Alloys

Certain copper alloys containing small amounts of beryllium, nickel and silicon, chromium, zirconium, and nickel and phosphorus are designated as heat treatable. These coppers are cold worked and then age hardened to tensile strengths considerably higher than brasses or bronzes. The most common and highly characterized of these alloys is beryllium copper (97.85Cu, 1.90Be, 0.25Co) which can be worked and aged to tensile strengths up to 200 000 psi. Springs, bellows, diaphrams, and bushings are commonly fabricated from this material. Care must be taken in use, because the impact strength of this material is uniformly low from -400° to 300° F, approximately six times lower than nickel-based alloys (such as Inconel 718) with equivalent strengths (ref. 23, vol. II, p. 226). In critical applications where brittle failure could constitute a hazard, a material such as aged Inconel X-750 or Monel K500 should be used in lieu of aged beryllium copper.

MISCELLANEOUS METALS

Several metals, most notably magnesium, titanium, and beryllium are found in aerospace structures because of their good strength to density ratio. The ignition and combustion of titanium and magnesium in oxygen have been widely studied.

Magnesium

Magnesium can be expected to ignite between 500° and 630° C at low oxygen pressures, or at 300° C below its melting point of 930° C (ref. 3, pp. 15 and 16). Apparently the protective oxide film on magnesium loses coherency at this relatively low temperature. Magnesium is also impact sensitive in LOX. Magnesium is therefore less safe than aluminum in oxygen systems and is not recommended for use.

Titanium

Titanium (and, to the same extent, zirconium) will resist ignition to near its melting temperature of 1940° C if the oxide film is not disturbed; however, sudden removal of the oxide film will cause ignition and violent combustion in room temperature and 350 psi pressure (ref. 3, pp. 6 to 12). The high heat of oxidation compounded by the very low thermal conductivity of these metals causes the near-instantaneous generation of high temperatures on the fresh surface. Combustion of titanium is not steady but marked by random violent explosions, perhaps due to failures caused by large thermal gradients due to the low thermal conductivity. These metals, or alloys containing major amounts thereof, are not safe in compressed oxygen or LOX systems where there is any possibility that the protective oxide film could be removed. Therefore, titanium and zirconium are not recommended for use.

Beryllium

The ignition temperature of beryllium in oxygen is within approximately 400° C of the melting point of beryllium oxide (3000° C), and is higher than the ignition temperature of aluminum (ref. 26, p. iv). However, the heat of formation of the oxide is extremely high (16 000 cal/g of beryllium compared to 7500 cal/g for aluminum) suggesting that a beryllium fire would be more energetic, therefore more hazardous, than any other fire involving a common metal of construction. In addition, beryllium metal, its oxides, and salts are highly toxic in transient concentrations higher than 25 micrograms per cubic meter of atmosphere (ref. 27, p. 76). Concentrations of this order are certainly possible in the event of a beryllium fire. For the previous reasons, beryllium should not be used in oxygen systems or near oxygen systems where it could be consumed in the event of a fire.

36

Gold and Platinum

The metal gold, and possible platinum, are the only metals where more energy is required to form the oxide film than is liberated by oxidation. In other words, these metals are not reactive with oxygen at room temperatures and this dissociation tendency further increases as temperature increases (ref. 3, p. i). This property allows gold and platinum to be used safely in oxygen systems where energy stimuli are high, perhaps high enough to ignite metals other than these. Electrical contacts, commutators and heater elements are some examples of these applications. The use of these metals as platings is perhaps more common than their use in bulk form. It is debatable whether plating can be relied upon for fire protection of a less compatible metal. Gold plating of electrical contacts will principally provide an oxide-free surface to facilitate electrical continuity. Loss of this plating will not only expose less compatible substrate metal, but will create oxide films, thereby increasing electrical resistance and contact temperature. If a fire would result with a loss of gold plating, solid gold substrate should be favored over gold plating.

IGNITION AND COMBUSTION OF METALS - RELATIVE COMPARISON

As with any material, the conditions necessary to enable a metal to ignite and burn involve a heat balance. If the rate of heating exceeds the rate of dissipation, the temperature will rise until either the protective oxide film fails or the metal beneath the film vaporizes and moves through the film to the oxygen resulting in combustion. The heat of formation of the oxide film contributes to the heat input and, together with the specific heat and thermal conductivity of the metal, influences the rise in temperature of the metal.

The shape, or more specifically the surface to volume ratio, of the metal influences the temperature rise due to heating. Sharp points such as burrs, metal particles, or powders do not contain much thermal capacity to prevent the generation of high temperatures. In fact, it is possible to divide a metal sample into small enough particles to cause combustion in oxygen by sudden exposure only: the heat liberated by surface oxide film formation is sufficient in itself. This is why it is important to provide smooth, continuous metal surfaces in oxygen systems and to assure that metal particles are not generated by operating wear or left in the system from fabrication processes.

It is of interest to understand how metals are relatively influenced by their properties to resist fire in oxygen. This is necessary to lend credence to the information in this report and to provide a means for appraisal of metals in oxygen where no prior experience exists. Unfortunately, an exact treatment of this subject is impossible because of the immense number of influencing factors. Attempts have been made (refs. 28

and 29) to calculate the ignition conditions for metals based on these influencing factors, but these are currently too theoretical to be of engineering value. A simplified approach is provided herein that (1) summarizes various metal ignition temperatures (as measured by test), (2) shows the metal properties that influence attainment of this temperature, and (3) lists the thermophysical properties of metals that are measures of the energy of combustion. Again, please remember that metal-oxygen fire hazards consist of (1) the ease with which the metal is ignited and (2) the violence of the fire, once ignited.

Symbols

		FPS units[1]	CGS units[1]	SI units[2]
c	specific heat	Btu/(lb)($^\circ$F)	cal/(g)($^\circ$C)	J/(kg)(K)
E	heat of oxide formation	Btu/lb metal	cal/g metal	J/kg metal
F_o	heat flux	Btu/(ft^2)(hr)	cal/(cm^2)(sec)	J/(m^2)(sec)
k	thermal conductivity	Btu/(hr)(ft)($^\circ$F)	cal/(sec)(cm)($^\circ$C)	J/(sec)(m)(K)
Q	heat of oxide formation		cal/g mol	J/kg mol
S	allowable working stress	psi or ksi	---------------	kg/m^2
T	surface temperature	$^\circ$F	$^\circ$C	K
T_{ign}	ignition temperature	$^\circ$F	$^\circ$C	K
t	time			
ρ	density	lb/ft^3	g/cm^3	kg/m^3

Influence of Metal Properties and Ignition Temperature

Relative energy rate to ignite. - Carslaw and Jaeger (ref. 30, p. 56) give the relation which describes the surface temperature of a semi-infinite solid subject to a given heat flux:

$$T = 2F_o \sqrt{\frac{t}{\pi k \rho c}}$$

(1)

---

[1]These units are typically given in the references and are therefore repeated in this report.

[2]These units are used in the original analysis of this report.

38

When rearranging terms it can be seen that

$$F_o\sqrt{t} \propto T\sqrt{k\rho c} \qquad (2)$$

If the flux F_o exists for a fixed time t (analogous to situations involving different metals subject to identical amounts of heating) and the ignition temperature T_{ign} is substituted for T, the relative resistance of the metal to ignition will be proportional to

$$T_{ign}\sqrt{k\rho c} \qquad (3)$$

Thus, metals with high values for T_{ign}, k, ρ, and c are more resistant to ignition than metals with low values of same. It must be noted that the previous does not consider the following:

(1) The physical boundaries of the metal object other than the flat surface receiving the heat flux are not considered. This is acceptable if the duration of heating is short or the object is massive. If not, three-dimensional, nonsteady heat conduction models must be resorted to such as given in reference 31 (pp. 331 to 436).

(2) The effect of surface (oxidation) reactions prior to ignition are not considered. If this precision is desired, techniques such as provided by reference 28 must be implemented.

Energy of combustion. - The heat of oxide formation such as is listed in reference 3 (p. 17) for various metals is also a relative measure of the heat liberated during combustion of the metal. The heats of formation Q are given in reference 3 in units of calories per gram mole of oxide. To convert these to E, the calories per gram of metal consumed (by fire) divide Q by the metal atomic weight times the number of metal atoms in the oxide molecule. For example, for aluminum, the oxide is Al_2O_3, Q is 1.68×10^9 joules per kilogram-mole, and the atomic weight is 26.98. Therefore, the heat liberated in an aluminum fire E is

$$E = \frac{1.68\times10^9}{2 \times 26.98} = 3.11\times10^7 \text{ J/kg metal} \qquad (4)$$

The previous is useful when comparing the potential fire severity of various metals comprising an equal weight structure. If various metals comprising an equal volume structure are to be compared, the value of E is multiplied by the metal density. For aluminum,

$$E\rho = 3.11\times10^7 \text{ J/kg metal} \times 2700 \text{ kg/m}^3$$

$$= 8.39\times10^{10} \text{ J/m}^3 \text{ metal} \tag{5}$$

If various metals comprising an equal strength structure are to be compared (perhaps the most realistic comparison), the value $E\rho$ is divided by S, the allowable working stress of the metal. For aluminum (assuming S = 7×10^5 kg/m^2)

$$\frac{E\rho}{S} = \frac{8.39\times10^{10}}{7\times10^5} = 1.20\times10^5 \frac{J}{(kg)(m)} \tag{6}$$

Thus, low strength metals can liberate more heat in a fire because more metal is necessary to provide the strength.

Summary comparison of various metals from the standpoints mentioned previously. - Table XIV lists the thermal and physical properties for several metals. Aluminum, steel, copper, and nickel are commonly used in oxygen systems and are discussed in this report. The metals magnesium, titanium, and silver are also included in this table for illustrative purposes. In the table, densities and specific heats are centervalues, and thermal conductivities are ranges based on the ranges of common alloy compositions and operating temperatures. Magnesium is known to ignite quite easily and burn quite energetically in oxygen. Titanium is a recognized ignition hazard in oxygen (see Miscellaneous Metals section). Conversely, silver is recognized as being superior in its resistance to fire in oxygen (ref. 4, p. 33), but it is too expensive for routine component fabrication. Figures 19 to 22 show the results of the previous calculations for the seven metals listed in table XIV. The following is apparent from examination of these figures:

(1) Figure 19: Aluminum is more difficult to ignite than steel. Copper and nickel are very difficult to ignite. Titanium is very easy to ignite. Silver is extremely difficult to ignite.

(2) Figures 20 to 22: Aluminum, magnesium, and titanium burn very energetically. Steel, copper, and nickel burn less energetically than aluminum. Silver burns the least energetically.

40

TABLE XIV. - SUMMARY OF THERMAL AND PHYSICAL PROPERTIES FOR SEVERAL METALS

Metal	Heat of oxide formation, Q, J/kg mol	Metal atomic weight	Number of metal atoms in oxide molecule	Density, kg/m³	Specific heat, c, J/(kg)(K)	Thermal conductivity range, k, J/(sec)(m)(K)	Minimum observed ignition temperature, T_{ign}, K	Allowable working stress range, S, kg/m²
Aluminum	168.0×10^7	26.98	2	2.70×10^3	938	104 to 243	920	0.14 to 1.0×10^6
Steel	26.6	55.85	1	7.87	503	12 to 42	1200	.70 to 1.8
Copper	17.5	63.54	2	8.96	385	104 to 390	1350	.21 to 1.5
Nickel	24.0	58.69	1	8.90	469	17 to 67	1720	.56 to 2.0
Magnesium	60.2	24.32	1	1.74	1026	71 to 109	880	.21 to 0.7
Titanium	94.5	47.90	1	4.50	578	4 to 17	1100	.56 to 1.1
Silver	3.01	107.90	2	10.49	234	209 to 419	could not ignite	.42 to 0.7
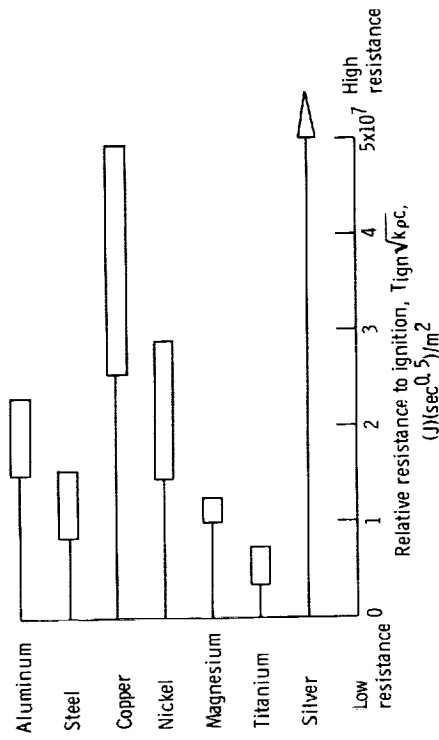
Figure 19. - Relative resistance to ignition.

Relative resistance to ignition, Tign√kρc, (J/sec^0.5)/m²

Figure 20. - Potential fire severity for equal weight (comparison of components of equal weight but made of different materials).

Potential fire severity for equal weight, E, J/kg

Figure 21. - Potential fire severity for equal volume (comparison of components of equal volume but made of different metals).

Potential fire severity for equal volume, Eρ, J/m³
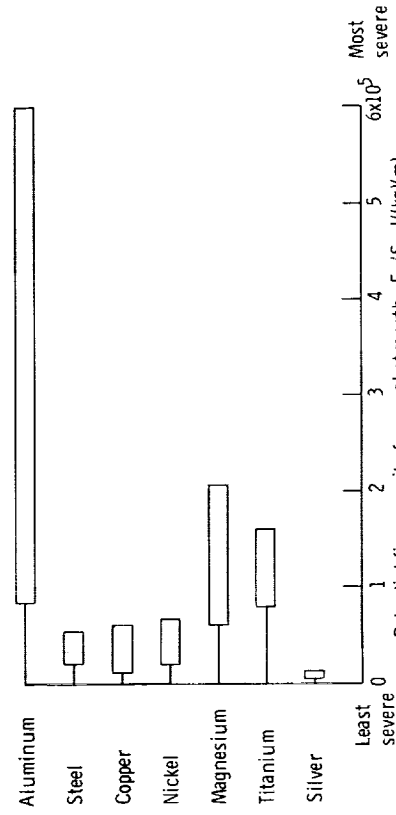
Figure 22. - Potential fire severity for equal strength (comparison of components of equal strength but made of different materials).

Potential fire severity for equal strength, Eρ/S, J/(kg)(m)

42

APPENDIX - TABLES OF SPECIFICATIONS, USES, AND SPECIAL CONSIDERATIONS FOR METALS AND ALLOYS IN OXYGEN SYSTEMS

TABLE A-I. - CORRELATION OF SPECIFICATIONS FOR STAINLESS STEELS[a]

Wrought alloys			Cast alloys		
AISI	SAE	ASTM	SAE	ACI	ASTM
Martensitic					
403	51403	Plate, sheet, strip: A176 Bars, billets: A276	--------	---------	-----
410	51410	Plate, sheet, strip: A176, A240 Bars, billets: A276 Pipe, tube: A268	60410	CA-15	A296
414	51414	Bars, billets: A276	--------	---------	-----
416, 416Se	51416, 51416Se	Bars, billets: A276	--------	---------	-----
420	51420	Bars, billets: A276	60420	CA-40	-----
431	51431	Bars, billets: A276	--------	---------	-----
440A, 440B, 440C	--------	Bars, billets: A276	--------	---------	A296
Ferritic					
405	51405	Plate, sheet, strip: A240 Bars, billets: A276 Pipe, tube: A268	--------	---------	A351
430, 430F, 430SeF	51430, 51430F, 51430SeF	Plate, sheet, strip: A176, A240 Bars, billets: A276 Pipe, tube: A268	--------	---------	-----
442	51442	Plate, sheet, strip: A176 Bars, billets: A276 Pipe, tube: A268	60442	CB-30	A296
446	51446	Plate, sheet, strip: A176 Bars, billets: A276 Pipe, tube: A268	70446	HC	A297
Austenitic					
301	30301	Plate, sheet, strip: A167, A264 (clad)	--------	---------	-----
302	30302	Plate, sheet, strip: A167, A240, A264 (clad) Bars, billets: A276, A314	--------	CF-20	A296
302B	30302B	Plate, sheet, strip: A167 Bars, billets: A276, A314	--------	HF	A297
303, 303Se	30303, 30303Se	Bars, billets: A276, A314 Nuts, bolts: A194, A320	--------	CF-16F	A296
304, 304L	30304, 30304L	Plate, sheet, strip: A167, A177, A240, A264 Bars, billets: A276, A314 Pipe, tube: A213, A249, A269, A270, A271, A312, A358, A376 Nuts, bolts: A193, A194, A320 Forgings, fittings: A182, A336	60304, 60304L	CF-8, CF-3	A296, A351
305	30305	Plate, sheet, strip: A240 Bars, billets: A314 Pipe, tube: A249	--------	---------	-----

[a]From information in ref. 7, p. 6.

TABLE A-I. - Concluded. CORRELATION OF SPECIFICATIONS FOR STAINLESS STEELS[a]

Wrought alloys			Cast alloys		
AISI	SAE	ASTM	SAE	ACI	ASTM
Austenitic					
308	30308	Plate, sheet, strip: A167, A264 Bars, billets: A276, A314 Welding electrodes: A298	--------	---------	-----
309, 309S	30309, 30309S	Plate, sheet, strip: A167, A240, A264 Bars, billets: A276, A314 Pipe, tube: A249, A312, A358 Welding electrodes: A298	60309, 70309	CH-20, HH	A296, A297, A351
310, 310S	30310, 30310S	Plate, sheet, strip: A167, A240, A264 Bars, billets: A276, A314 Pipe, tube: A213, A249, A312, A358 Forgings, fittings: A182, A336 Welding electrodes: A298	60310, 70310	CK-20, HK	A296, A297, A351
314	30314	Bars, billets: A314	--------	---------	-----
316, 316L	30316, 30316L	Plate, sheet, strip: A167, A240, A264 Bars, billets: A276, A314 Pipe, tube: A213, A249, A269, A312, A358, A376 Nuts, bolts: A193 Forgings, fittings: A182, 336 Welding electrodes: A298	60316, 60316L	CF-3M, CF-8M, CF-12M	A296 A351
317	30317	Plate, sheet, strip: A240 Bars, billets: A314 Pipe, tube: A249, A269, A312 Welding electrodes: A298	60317	CG-8M	A296
321	30321	Plate, sheet, strip: A167, A240, A264 Bars, billets: A276, A314 Pipe, tube: A213, A249, A269, A271, A312, A358, A376 Nuts, bolts: A193, A194, A320 Forgings, fittings: A182, A336	--------	---------	-----
347	30347	Plate, sheet, strip: A167, A240, A264 Bars, billets: A276, A314 Pipe, tube: A213, A249, A269, A271, A298, A358, A376 Nuts, bolts: A193, A194, A320 Forgings, fittings: A182, A336 Welding electrodes: A298	60347	CF-8C	A296, A351
348	30348	Plate, sheet, strip: A240 Bars, billets: A276, A314 Pipe, tube: A213, A249, A269, A358, A376 Nuts, bolts: A320	--------	---------	-----

[a] From information in ref. 7, p. 6.

44

TABLE A-II. - SPECIAL CONSIDERATIONS FOR STAINLESS STEEL ALLOYS[a]

(a) FeA steels

Steel	Special considerations

Types 301, 302:
 	
    Fe
18   Cr
8   Ni
	The effect of cold work on the properties of these steels, particularly of type 301, depends to a considerable extent on the content of nickel, carbon, and possibly other elements, as well as on not well recognized processing conditions, such as speed and temperature of rolling. Materials can be obtained for special requirements to closer composition on limits than those listed in specifications in order to secure higher uniformity in properties or performance on fabrication.
	  Cold rolled sheet in these alloys exhibits a very pronounced directionality. While the tensile strength and tensile yield strengths are nearly the same in both directions, the compressive yield strength and compressive stress strain curves are much higher in the transverse than in the longitudinal direction. This condition is only partly improved by stress relief.
	  Small amount of cold work during straightening and handling can raise considerably the low yield strength of annealed material. Heating for long times at 800° F and short times at 1600° F or slow cooling through this range must be avoided. Carburizing conditions at high temperature reduce corrosion resistance. Adhering zinc and lead particles which lead to embrittlement at elevated temperatures must be removed prior to heating.

Types 304, 304L: Fe Low C 19 Cr 10 Ni	Intergranular corrosion after welding or heating may occur in type 304, but usually not in type 304L.

19-9 DL 8, 19-9 DX:
 	
    Fe
20   Cr
10   Ni
1.5 Mo
1.5 W
	Alloy is susceptible to stress cracking after forming unless stress relieved or annealed. Heat at temperatures in the vicinity of 1100° to 1200° F sensitizes the alloy (i. e., develops susceptibility to intergranular attack).
	  Alloy may crack after cold work or welding unless annealed or stress relieved.

Types 310, 310S:
 	
    Fe
24   Cr
20   Ni
	Intergranular carbide precipitation can occur after prolonged heating in the range between 800° and 1600° F, on slow cooling through this range. The tendency to carbide precipitation will be reduced by lowering the carbon content (as in 310S) and this grade is preferred for welding or when the service condition could promote carbide precipitation. Sigma formation can occur during prolonged heating in the temperature range between 1200° and 1800° F. The tendency to form sigma will be increased by cold work. The amount of sigma formed in this alloy is much less than in silicon containing grades such as 312.
	  The alloy is free from LOX temperature strain induced phase changes which can produce embrittlement in the lower nickel grades (e.g., 301 and 302). The crack propagation resistance at cryogenic temperatures is excellent in longitudinal direction even for heavily cold worked material. However, such material is characterized by a pronounced mechanical anisotropy and the crack propagation resistance is considerably lower in the transverse than in the longitudinal direction.

Type 314: Fe 25 Cr 20 Ni 2 Si	Prolonged exposure at 1200° to 1600° F may cause embrittlement through carbide precipitation and sigma phase formation. Ductility may be restored by annealing at 1900° to 1950° F for 10 to 60 minutes. This treatment is recommended after a 1000-hour exposure at 1400° to 1600° F.
Types 316, 317: Fe 18 Cr 13 Ni + Mo	Prolonged heating at temperatures from 800° to 1600° F may result in embrittlement and stress corrosion sensitivity. Because of its reduced stress corrosion sensitivity, type 316L is recommended when heavy cross sections cannot be annealed after welding or where low temperature stress relieving is desired.

Type 321:
 	
    Fe
18   Cr
10   Ni
+   Ti
	Heating above 1900° F followed by heating about 1200° F may sensitize this steel.
	  Use type 347 welding wire for shielded-metal-arc welding type 321 to prevent loss of stabilization.
	  Cold work greatly reduces the deep ductility at 1100° and 1200° F, particularly if grain size is less than 5. Annealing is recommended to restore the ductility.

[a]From information in ref. 6, secs. 13XX to 16XX.

45

(b) FeM steels

Steel	Special considerations

Types 403, 410, 416:
      Fe
 Low   C
 12   Cr
	Avoid temperating at 550° to 1050° F because of reduced resistance to stress corrosion and increased notch sensitivity.
	     Corrosion resistance of type 410 castings may not be satisfactory for many applications. Casting quality should be evaluated by penetrant inspection rather than by magnetic inspection, because of inconsistency of the latter method. Type 416 castings are primarily used for small parts at temperatures up to 1000° F. Corrosion resistance is lower than that of type 410 castings but machinability is better. The proper chemical balance is necessary in types 403 and 410 to ensure against the formation of free or delta ferrite which can affect the mechanical properties, especially hardness and toughness. The hardness decreases with an increase in the free ferrite content while the toughness as measured by impact strength increases for longitudinal tests but decreases for transverse tests. These effects on impact strength are due to the mechanical fibering associated with the presence of free ferrite and their magnitude will depend on both the amount of ferrite present and the degree of work in the structure.

Type 420: Fe Med C 13 Cr	See also type 410. Stress corrosion may occur if the steel is exposed at 700° to 800° F. It should not be used for heavily stressed parts that will operate at subzero temperatures.
Type 422: Fe 12 Cr 1 Mo 1 W 0.8 Ni 0.25 V	See type 420.

Type 431:
      Fe
 0.2   C
 16   Cr
 2   Ni
	The composition of this steel is such that difficulties are sometimes encountered in obtaining the expected mechanical properties. The high chromium content tends to keep the structure ferritic during austenitizing. This tendency is overcome by the addition of nickel which tends to promote austenite formation. However, the composition limits are rather broad, and significant variations in response to heat treatment and mechanical properties can be expected within the normal ranges of chemistry. If the chromium is high and the nickel low, the quenched steel may contain ferrite and not develop full strength. If the chromium is low and the nickel high, retained austenite may be a problem and subcooling after quenching will be required. In such cases it is recommended to refrigerate rather than water quench to avoid potential cracking. Carbon contents on the high side tend to increase tensile strength but lower the corrosion resistance. Castings are available in more than one range of carbon contents. Stress relief or tempering in the range between 700° to 1100° F is not recommended since embrittlement in this range may be encountered.
	     Hydrogen embrittlement may be a problem with this steel at high hardness and strength levels.

Type 440A, B, and C: Fe High C 17 Cr 0.5 Mo	Cracking may occur on heating, cooling, pickling or after welding. Steels are particularly subject to decarburization because of high carbon content.
USS-12 MoV: Fe 12 Cr 1 Mo 0.65 Ni 0.3 V	See types 410 and 420. This material is susceptible to stress-corrosion cracking when stressed and simultaneously exposed to some corrosive environment.

[a]From information in ref. 6, secs. 13XX to 16XX.

(c) FeAH steels

Shell		Special considerations
17-4 PH:		No special precautions are necessary for this alloy except the need for cleanliness as for any stainless steel. The alloy also has a wide allowance in compositional range.
	Fe	
17	Cr	
4	Ni	
4	Cu	
17-7 PH:		The crack propagation resistance as measured by the sharp notch strength exhibits a pronounced minimum at aging temperature between 900° and 1050° F. This is the region of aging temperature producing the highest strength and having the greatest commercial interest. Very high toughness at considerable sacrifice in strength can be obtained by over-aging at temperatures of 1100° F and above. The impact strength of all heat treated conditions of this alloy decrease at subzero temperatures. At a given low test temperature the impact strength increases with aging temperature but at cryogenic temperatures only the overaged relatively low strength conditions exhibit a useful degree of toughness. Poor crack propagation resistance at subzero temperatures is indicated by K_{Ic} values ranging from about 40 to 50 ksi-in.$^{1/2}$ at -50° F.
	Fe	
17	Cr	
7	Ni	
1	Al	
		The room temperature tensile strength of the heat treated conditions increases with exposure to temperatures between about 600° to 900° F. Tensile tests at elevated temperatures show the same effects of exposure. It might be expected that this increase in strength would be accompanied by a decrease in crack propagation resistance. Such an embrittling effect is noted for PH14-8Mo.
		The crack propagation resistance is lower in the transverse than in the longitudinal direction. Cold work following heat treatment to condition A and subsequent to aging can produce large reductions in tensile properties as compared with those that would be obtained in the absence of the cold work. Dimensional changes during heat treatment require special consideration. There is a volume contraction on hardening.
PH15-7Mo:		Alloy is available in numerous forms, but the primary usage is in the sheet and strip form. In common with the general class of precipitation hardening stainless steels, this alloy is unstable during exposure to temperatures exceeding about 500° F. This instability is reflected in an increase in the yield strength and a decrease in fracture toughness. The transverse direction has lower toughness than the longitudinal direction.
	Fe	
15	Cr	
7	Ni	
2.5	Mo	
		Dimensional changes during heat treating to conditions TH 1050 or RH 950 need consideration and special provisions must be made for machining and tooling. Thorough cleaning prior to thermal treatments is recommended in order to avoid carburization and to minimize difficulties when descaling.
AM 350:		Heating to temperature above those specified for condition H should be avoided because of excessive delta ferrite formation and loss of response to hardening.
	Fe	Annealing of heavy bar and forging to condition H may result in loss of response to heat treating.
17	Cr	Forging of heavy sections should be finished at about 1750° F to ensure adequate response to heat treating.
4	Ni	CRT (cold-rolled, tempered condition alloy) has optimum stress corrosion resistance. SCT (subcooled, tempered condition alloy) requires either a minimum of 10 percent delta ferrite or a 1000° F temper for optimum stress corrosion resistance.
3	Mo	
AM 355:		Heating to temperatures above those specified for condition H (anneal) should be avoided because of grain coarsening and less of response to hardening. AM 355, when hardened by the carbide solution subzero treatment, has stress corrosion resistance superior to that of AM 350 in the SCT (850) condition and comparable to that of AM 350 in the SCT (1000) condition.
	Fe	
15.5	Cr	
4.5	Ni	
3	Mo	
PH14-8Mo:		When PH14-8Mo is fabricated in condition A (anneal), and subsequently heat treated, an allowance should be made for the dimensional change (an overall expansion of approximately 0.004 in./in.) that occurs during heat treatment. Thorough cleaning prior to thermal treatments is recommended in order to avoid carburization and to minimize difficulties when descaling.
	Fe	
14	Cr	
8	Ni	
2.5	Mo	This alloy exhibits a metallurgical instability which is manifest as an increase in the tensile yield strength and decrease in the static crack propagation resistance when cracked or sharply notched specimens are exposed for long periods of time at moderately elevated temperatures and then tested at the exposure temperature or at a lower temperature. These instability effects are not reduced by vacuum melting and appear to be larger the higher the strength level of the material. There is insufficient data to establish the time-
	Al	

[a]From information in ref. 6, secs. 13XX to 16XX.

(c) Continued. FeAH steels

Steel		Special considerations
		temperature relation for the effect of the instability on the mechanical properties; however, it would appear that exposure at temperatures below about 400° F produces negligible embrittlement. In general, the longitudinal direction of sheet has a higher toughness than the transverse direction. However, this directionality is reduced by vacuum melting. The alloy has poor fracture toughness below about -200° F and should not be used at cryogenic temperatures.
AF 71:		The high quenching temperature of 2050° F has been considered by some consumers to be objectionable
	Fe	in the processing of material in thin gages because of the excessive thickness loss incurred in scaling and
18	Mn	pickling. To avoid such losses expensive heat treating equipment (vacuum furnaces or controlled-
12	Cr	atmosphere furnaces) are required.
3	Mo	
+	V	
+	B	
PH13-8Mo:		The fracture toughness of this alloy is good in heavy sections at room temperature and above but de-
	Fe	creases rapidly at temperatures below about 0° F. Heavy sections appear to exhibit negligible direction-
13	Cr	ality of tensile properties. Insufficient data are available to define the directionality of fracture toughness;
8	Ni	however, limited information indicates that it is probably small. In common with other alloys of this
2	Mo	class the impact strength and presumably the fracture toughness decrease as a result of long time exposure to moderately elevated temperature. It should be noted that nearly all information available for this chapter relates to the double vacuum melted product. Lower toughness and greater directionality can be expected of air-melted material.
AFC 77:		This alloy is subject to a severe embrittlement when tempered above about 700° F. The tempering tem-
	Fe	perature range over which this embrittlement occurs is much more extensive than in other FeM stainless
0.15	C	steels and extends to nearly 1400° F. No substantial recovery in the embrittlement is noted for 1200° F
14.5	Cr	tempering even though this temperature is well beyond the secondary hardening peak. Cold rolling pre-
13.5	Co	ceding tempering in the brittle range can substantially increase the strength but also increases the embrit-
5	Mo	tlement. The alloy is not stable during elevated temperature exposure and long time exposures to moder-
0.5	V	ately elevated temperatures can substantially increase the embrittlement. As might be expected, the low
0.05	N_2	temperature crack and notch strength are very poor for conditions tempered in the brittle range.
		If tempering is confined to temperatures below about 700° F, the yield strength is below about 170 ksi and the room temperature fracture toughness is high. No valid values of K_{Ic} are available for these tempered conditions. It would be expected that the low tempered conditions would not be stable during elevated temperature exposure, and that a time temperature dependent embrittlement would develop.
AM 362:		This alloy like the conventional 12Cr steels is subject to an embrittlement when held for long times at
	Fe	temperatures between 700° and 1000° F. This is also reflected in low impact strength for tempering
15	Cr	temperatures below about 1000° F. The toughness of the alloy is strongly influenced by the titanium con-
7	Ni	tent and decreases with increasing titanium.
	Ti	
15-5 PH:		Precipitation-hardening stainless steel alloys are used in many applications requiring large and medium
	Fe	size sections. In many cases, loading transverse to the fiber is involved. It has been demonstrated that
15	Cr	certain structural characteristics, particularly delta ferrite and some precipitates, cause substantial re-
5	Ni	ductions in transverse ductility, and presumably fracture toughness, for many of these alloys. For com-
4	Cu	positions in which delta ferrite is present, vacuum remelting does not improve this situation.
		15-5 PH is a delta ferrite-free compositional modification of 17-4 PH alloy containing less chromium and slightly higher nickel. Its short-transverse ductility at edge and intermediate locations is superior to 17-4 PH in heavy sections. However, in products made from air-cast ingots of 15-5 PH, the short transverse ductility at the center location may be lower than at edge or intermediate locations. This nonuni- formity of ductility is evidently the result of gross segregation which may be reduced by vacuum remelting. Martensitic and precipitation-hardening stainless steels are subject to an embrittling reaction when heated between about 500° to 900° F. This is evidenced by an increase in yield strength and a reduction in the resistance to crack propagation. Its magnitude depends on a number of factors including the exposure time, composition, and previous treatment.

[a]From information in ref. 6, secs. 13XX to 16XX.

TABLE A-II. - Concluded. SPECIAL CONSIDERATIONS FOR STAINLESS STEEL ALLOYS[a]

(c) Concluded. FeAH steels

Steel		Special considerations
		Insufficient data are available to quantitatively define the effects of these variables for any of the commercial steels subject to this embrittlement. However, on the basis of the information available for the PH steels, it would be expected that long time exposures at temperatures in the lower portion of the embrittling range would produce the maximum embrittling effects.
		It has been reported that the embrittling is associated with the formation of a copper-rich alpha prime ferrite phase and that the following factors are important in establishing its magnitude:
		1. Increased amounts of chromium, silicon and columbium increase the rate of embrittlement at 800° F. When silicon and columbium are low, chromium becomes the sole controlling factor, except that the nickel content as related to the chromium influences the result (Cr-Ni balance influences the martensite reaction). The highest nickel content which can be used at a given level of chromium without inhibiting martensite transformation is best from the standpoint of embrittlement.
		2. The embrittlement is completely reversible by reapplying the initial precipitation hardening temperature, if that temperature is 1025° F or higher.
		3. Lowering the solution-treating temperature, at least down to 1650° F, slightly lessens the tendency toward embrittlement at 800° F.
		Consumers have sometimes complained that the composition limits of precipitation-hardenable semi-austenitic steels are too wide to permit uniform response to heat treatment. The impact strength of 17-4 PH type precipitation-hardening stainless steel both before and after exposure at 800° F are affected by variations in chemistry within the recommended composition range. It would be expected that 15-5 PH would be similarly affected. For many applications, 15-5 PH should not be used in condition A. This is true even though the desired hardness may fall within the range of condition A. While the alloy is relatively soft in condition A, the structure is untempered martensite that has low ductility and poor resistance to stress corrosion cracking.
N-155:		Unless stress relieved, hot cold-worked forgings may warp during machining.
	Fe	
20	Co	
20	Cr	
20	Ni	
3	Mo	
2.5	W	
1	Cb	
S-590:		Avoid large grain forgings.
	Fe	
20	Co	
20	Cr	
20	Ni	
4	Cb	
4	Mo	
4	W	
16-25-6:		Avoid heating alloy to high temperatures in stagnant oxidizing atmosphere, because of molybdenum reactions.
	Fe	
25	Ni	
16	Cr	
6	Mo	
Incoloy:		At 1800° F the scaling resistance of Incoloy is comparable to that of the high nickel alloys such as Inconel and Nimonic 75.
	Fe	
34	Ni	
20	Cr	
Incoloy alloy 802:		This alloy is not recommended for use at temperatures above 1700° F. Dispersion reactions in the temperature range between about 1200° and 1600° F reduce the tensile elongations and impact strength.
	Fe	
0.35	C	
33	Ni	
21	Cr	
0.75	Ti	
0.60	Al	

[a]From information in ref. 6, secs. 13XX to 16XX.

TABLE A-III – SPECIFICATIONS AND FORMS FOR WROUGHT ALUMINUM ALLOYS*

Commercial Designation	Sheet and Plate	Drawn Tube	Pipe and Round Seamless Extruded Tube	Welded Tube	Extruded Bar, Rod, Shapes, and Tube	Bar, Rod, Wire, and Shapes Rolled or Drawn Spray Wire	Brazing or Welding Rod and Electrode	Rivets and Rivet Wire	Forgings and Forging Stock
1100	QQ-A-250/1 AMS 4001 AMS 4003 ASTM B209 USA H38.2	WW-T-700/1 AMS 4062 ASTM B307 ASTM B210 USA H38.3	ASTM B241 USA H38.7	ASTM B313 USA H38.11	ASTM B221 USA H38.5	QQ-A-225/1 MIL-W-6712 AMS 4102 AMS 4180 ASTM B211 USA H38.4	QQ-R-566 MIL-E-15597 MIL-E-16053 ASTM B285 ASTM B184	MIL-R-5674 QQ-A-430 AMS 7220 ASTM B316 USA H38.12	ASTM B247 USA H38.8
1230									
2011						QQ-A-225/3 ASTM B211 USA H38.4			
2014	AMS 4028 AMS 4029 AMS 4014 ASTM B209 USA H38.2	ASTM B210 USA H38.3	ASTMB241 USA H38.7		QQ-A-200/2 AMS 4153 ASTM B221 USA H38.5	QQ-A-225/4 AMS 4121 ASTM B211 USA H38.4			QQ-A-367 AMS 4134 AMS 4135 ASTM B247 MIL-A-22771 USA H38.8
Alclad 2014	QQ-A-250/3 ASTM B209 USA H38.2								
2017						QQ-A-225/5 AMS 4110 AMS 4118 ASTM B211 USA H38.4		MIL-R-5674 QQ-A-430 ASTM B316 USA H38.1	
2024	AMS 4033 AMS 4035 AMS 4037 AMS 4097 AMS 4098 AMS 4099 AMS 4103 AMS 4104 AMS 4105 AMS 4106 QQ-A-250/4 ASTM B209 USA H38.2	WW-T-700/3 AMS 4087 AMS 4088 AMS 4086b ASTM B210 USA H38.3	ASTM B241 USA H38.7		QQ-A-200/3 AMS 4152 AMS 4164 AMS 4165 ASTM B221 USA H38.5	QQ-A-225/6 AMS 4112 AMS 4119 AMS 4120 ASTM B211 USA H38.4		MIL-R-5674 QQ-A-430 ASTM B316 AMS 7223 USA H38.12	
Alclad 2024	QQ-A-250/5 AMS 4034 AMS 4040 AMS 4041 AMS 4042 AMS 4060 AMS 4061 AMS 4072 AMS 4073 AMS 4074 AMS 4075 ASTM B209 USA H38.2								
2117								USA H38.12 MIL-R-27384 MIL-R-5674 MIL-R-8814 AMS 7222 ASTM B316 QQ-A-430	
2219	MIL-A-8920 ASTM B209 USA H38.2 AMS 4031		ASTM B241 USA H38.7		ASTM B221 USA H38.5	ASTM B211 USA H38.4			ASTM B247 QQ-A-367 AMS 4143 AMS 4144 USA H38.8
Alclad 2219	ASTM B209 USA H38.2								
3003	QQ-A-250/2 AMS 4006 AMS 4008 ASTM B209 USA H38.2	WW-T-700/2 AMS 4065 AMS 4067 ASTM B210 ASTM B234 ASTM B307 USA H38.9 USA H38.6 USA H38.3	ASTM B241a ASTM B345a MIL-P-25995 USA H38.7 USA H38.13	ASTM B313 USA H38.11	QQ-A-200/1 ASTM B221 USA H38.5	QQ-A-225/2 ASTM B211 USA H38.4	MIL-E-15597	MIL-R-1150 QQ-A-430	ASTM B247 USA H38.8

*From information in ref. 17, pp. 162 to 164.

TABLE A-III – Concluded. SPECIFICATIONS AND FORMS FOR WROUGHT ALUMINUM ALLOYS*

Commercial Designation	Sheet and Plate	Drawn Tube	Pipe* and Round Seamless Extruded Tube	Welded Tube	Extruded Bar, Rod, Shapes, and Tube^	Bar, Rod, Wire, and Shapes Rolled or Drawn^c Spray Wire	Brazing or Welding Rod and Electrode	Rivets and Rivet Wire	Forgings and Forging Stock
5457	ASTM B209 USA H38.2								
5557	ASTM B209 USA H38.2								
5657	ASTM B209 USA H38.2								
6061	QQ-A-250/11 AMS 4025 AMS 4026 AMS 4027 ASTM B209 USA H38.2	WW-T-700/6 AMS 4079 AMS 4080 AMS 4081b MIL-T-7081b AMS 4082 AMS 4083b ASTM B210 ASTM B234 USA H38.3 USA H38.6	ASTM B241a ASTM B345a MIL-P-25995 USA H38.7 USA H38.13 ASTM B429	ASTM B313 USA H38.11	QQ-A-200/8 AMS 4150 AMS 4160 AMS 4161 ASTM B221 USA H38.5	QQ-A-225/8 ASTM B211 AMS 4115 AMS 4116 AMS 4117 USA H38.4		QQ-A-430 ASTM B316 USA H38.12 MIL-R-1150	QQ-A-367 AMS 4127 AMS 4146 ASTM B247 USA H38.8 MIL-A-22771
Alclad 6061	AMS 4020 AMS 4021 AMS 4022 AMS 4023 ASTM B209 USA H38.2								
6063		ASTM B210 USA H38.3	ASTM B241a ASTM B345a MIL-P-25995 USA H38.7 USA H38.13		QQ-A-200/9 AMS 4156 ASTM B221 USA H38.5				
6151									QQ-A-367 AMS 4125 ASTM B247 USA H38.8
6262		ASTM B210 USA H38.3			ASTM B221 USA H38.5	QQ-A-225/10 ASTM B211 USA H38.4			
6463					ASTM B221 USA H38.5				
6951									
7039	ASTM B209 USA H38.2								
7072									
7075	QQ-A-250/12 AMS 4038 AMS 4044 AMS 4045 AMS 4078 ASTM B209 USA H38.2	ASTM B210 USA H38.3	ASTM B241 USA H38.7		USA H38.5 QQ-A-200/11 AMS 4154 AMS 4167 AMS 4168 AMS 4169 ASTM B221	QQ-A-225/9 AMS 4122 AMS 4123 AMS 4124 ASTM B211 USA H38.4		ASTM B316 QQ-A-430 USA H38.12	QQ-A-367 AMS 4139 AMS 4141 ASTM B247 MIL-A-22771 USA H38.8
Alclad 7075	QQ-A-250/13 AMS 4039 AMS 4048 AMS 4049 AMS 4047d ASTM B209 USA H38.2								
7079	QQ-A-250/17 AMS 4024 ASTM B209 USA H38.2		ASTM B241 USA H38.7		QQ-A-200/12 AMS 4171 ASTM B221 USA H38.5				QQ-A-367 MIL-A-22771 AMS 4138 AMS 4136 ASTM B247 USA H38.8
7178	QQ-A-250/14 ASTM B209 USA H38.2		ASTM B241 USA H38.7		AMS 4158 QQ-A-200/13 ASTM B221 USA H38.5			MIL-R-24243	
No. 11 Brazing Sheet									
No. 12									
No. 21									
No. 22									
No. 23									
No. 24									

* Pipe made by any process.
b Tube Hydraulic.
c Includes Structural Shapes.
d Plate and Sheet Roll tapered.

*From information in ref. 17, pp. 162 to 164.

TABLE A-III – Continued. SPECIFICATIONS AND FORMS FOR WROUGHT ALUMINUM ALLOYS*

Commercial Designation	Sheet and Plate	Drawn Tube	Pipe and Round Seamless Extruded Tube	Welded Tube	Extruded Bar, Rod, Shapes, and Tube	Bar, Rod, Wire, and Shapes Rolled or Drawn Spray Wire	Brazing or Welding Rod and Electrode	Rivets and Rivet Wire	Forgings and Forging Stock
Alclad 3003	ASTM B209 USA H38.2	ASTM B210 ASTM B234 ASTM B307 USA H38.3 USA H38.6 USA H38.9	ASTM B241 ASTM B345ª USA H38.7 USA H38.13		ASTM B221 USA H38.5				
3004	ASTM B209 USA H38.2	ASTM B210 ASTM B307 USA H38.3 USA H38.9		ASTM B313 USA H38.11	ASTM B221 USA H38.5				
Alclad 3004	ASTM B209 USA H38.2			ASTM B313 USA H38.11					
4032									QQ-A-367 AMS 4145 ASTM B247 USA H38.8
4043						MIL-W-6712 (Spray Gun Wire)	QQ-B-655 QQ-R-566 MIL-E-15597 MIL-E-16053 AMS 4190 ASTM B184 ASTM B260 ASTM B285		
4343							QQ-B-655 MIL-B-20148		
5005	ASTM B209 USA H38.2	ASTM B307 USA H38.9				ASTM B396 (Electrical Wire)		QQ-A-430	
5050	ASTM B209 USA H38.2	ASTM B210 ASTM B307 USA H38.3 USA H38.9	ASTM B345ª	ASTM B313 USA H38.11					
5052	QQ-A-250/8 AMS 4015 AMS 4016 AMS 4017 ASTM B209 USA H38.2	WW-T-700/4 AMS 4069 AMS 4070 AMS 4071 ASTM B210 ASTM B307 ASTM B234 USA H38.3 USA H38.13	ASTM B345ª USA H38.13	ASTM B313 USA H38.11	ASTM B221 USA H38.5	QQ-A-225/7 AMS 4114 ASTM B211 USA H38.4		QQ-A-430 ASTM B316 USA H38.12 MIL-R-24243	
5083	QQ-A-250/6 ASTM B209 AMS 4056 AMS 4057 AMS 4058 AMS 4059 USA H38.2	ASTM B210 USA H38.3	ASTM B241ª ASTM B345ª USA H38.7 USA H38.13		QQ-A-200/4 ASTM B221 USA H38.5				ASTM B247 QQ-A-367 USA H38.8
5086	QQ-A-250/7 ASTM B209 USA H38.2	WW-T-700/5 ASTM B210 USA H38.3	ASTM B241ª ASTM B345ª USA H38.7 USA H38.13	ASTM B313 USA H38.11	QQ-A-200/5 ASTM B221 USA H38.5				
5154	AMS 4018 AMS 4019 ASTM B209 USA H38.2	ASTM B210 USA H38.3	ASTM B345ª ASTM B241ª MIL-P-25995 USA H38.13 USA H38.7	ASTM B313 USA H38.11	ASTM B221 USA H38.5	ASTM B211 USA H38.4	MIL-E-16053 ASTM B285 QQ-R-566		
5252	ASTM B209 USA H38.2								
5454	QQ-A-250/10 ASTM B209 USA H38.2	ASTM B234 USA H38.6	ASTM B241ª MIL-P-25995 USA H38.7		QQ-A-200/6 ASTM B221 USA H38.5				
5456	QQ-A-250/9 ASTM B209 USA H38.2		MIL-P-25995 ASTM B241ª ASTM B345ª USA H38.7 USA H38.13		QQ-A-200/7 ASTM B221 USA H38.5				ASTM B247 USA H38.8

*From information in ref. 17, pp. 162 to 164.

As shown in table A-IV, the standard temper designation system for aluminum and aluminum alloys, both wrought and cast, consists of a letter indicating the basic temper which, except for the annealed and as-fabricated tempers, is more specifically defined by adding one or more digits. The four main basic tempers are as follows: O, annealed; F, as-fabricated; H, strain hardened; and T, heat treated. The symbol W is used to designate the unstable condition following solution heat treatment, and if time subsequent to heat treatment is indicated, it may be considered a basic temper. It is a principle of this system that a change in a temper designation is made only when some variation in the same basic operation significantly alters the characteristics of the product.

TABLE A-IV. - TEMPER DESIGNATION SYSTEM FOR ALUMINUM ALLOYS[a]

Designation	Description
F As-fabricated	Designation applies to products supplied in the condition resulting from normal manufacturing operations, without special practices to control the amount of strain or thermal treatment. For wrought products, there is no guarantee of mechanical properties. For castings, the term means as-cast. An example of 43-F.
H Strain hardened	Designation applies to those wrought products that are not subjected to thermal treatments to increase their mechanical properties but that have their strength increased by strain hardening, with or without supplementary thermal treatment to produce partial softening. The H is always followed by two or more digits. First digit indicates the specific combination of basic operations and the following digit or digits the final degree of strain hardening. (The digital system is explained subsequently.)
H1__ Strain hardened only	As indicated previously, the second digit designates the amount of cold work performed. The digit 8 has been selected to represent the hardest commercially practical temper, written as H18. Material with tensile strength halfway between soft and full hard, half hard, is designated H14; quarter hard, H12; and so on.
	A third digit is often used to identify a special set of properties. For example, H141 may represent the same minimum properties as H14, but with maximum values that are closer than standard. The third digit may also denote values slightly different from those of H14, but not sufficiently different to place it in the H13 or H15 classification.
	Extra hard tempers are designated by using the second digit 9, with or without a third digit. The H112 temper for wrought alloys is generally considered a "controlled" F-temper with guaranteed mechanical properties.
H2__ Strain hardened and partial annealed	It is often desirable to obtain a certain strength range in the strain hardened alloys by working to a harder temper and then reducing the strength to the desired level by partial annealing. This process is identified by the number 2 in the first digit place, and the residual amount of cold work is then designated by the same method employed for the H1 series. Thus, H28 is full hard, H24 half hard, and so on. For alloys that age soften at room temperature, the H2 tempers have approximately the same tensile strength as the corresponding H3 tempers. For other alloys, the H2 tempers have approximately the same tensile strength as the corresponding H1 tempers and slightly higher elongations.
H3__ Strain hardened and then stabilized	The properties of magnesium-containing alloys in the strain hardened condition are stabilized by a low-temperature hearing, thus slightly lowering their strength and increasing their ductility. If the treatment is not employed, then the change of properties occurs over a long time at room temperature. Use of this treatment is indicated by the digit 3 following the H, and the degree of strain hardening is indicated in the usual way by one or two following digits.
O Annealed, recrystallized	Designation applies to the softest temper of wrought alloy products.

[a]Information from ref. 5, pp. 888 and 889.

Designation		Description
T	Treated to produce stable tempers other than F, O, or H	Designation applies to products thermally treated to produce stable tempers with or without supplementary strain hardening. The T followed by the numerals 2 to 9 inclusive, designates one specific combination of basic operations, thus 6061-T6. Should variation of the same basic operation be applied to the same alloy, resulting in different characteristics, other digits are added to the basic designation (6061-T61 or 6061-T62). It should be understood that a period of natural aging at room temperature may occur between or after the operations listed. Control of this period is exercised when it is metallurgically important, but it is not indicated by the designation. Basic subdivisions of the T-temper, ranging from annealing to complex aging treatments, are now given.
T2	Annealed (cast products only)	Designation applies to castings only. Annealing is used for such purposes as improving ductility and increasing dimensional stability.
T3	Solution heat treated and cold worked, naturally aged to substantially stable condition	Designation applies to those wrought products that are cold worked for the primary purpose of improving the strength (for instance, 2024-T36) and also applies to those products in which the effect of cold work, such as flattening or straightening, is recognized in applicable specifications (flat sheet of 2024 heat treated by the supplies is designated 2024-T3). No control is exercised to cold work at any particular stage during the natural aging cycle.
T4	Solution heat treated and naturally aged to a substantially stable condition	Designation applies when the product is not cold worked after heat treatment (2024 sheet heat treated by the user becomes 2024-T4), and also when applicable specifications do not recognize the effect of cold work resulting from flattening and straightening operations (6061 flat sheet heat treated by the supplier is designed 6061-T4). The alloy 7075 does not have a commercial T4 designation. (An example for a casting alloy is 195-T4.)
T5	Artificially aged only	Designation applied to products that are artificially aged without prior solution heat treatment. The artificial aging of these products improves mechanical properties (6063-T5 extrusions) and dimensional stability (D132-T4 castings).
T6	Solution heat treated and then artificially aged	Designation applies to products that are not cold worked after solution heat treatment or in which the effect, if any, of flattening or straightening is not recognized inapplicable specifications. Whether flattened or not, 6061 heat treated and aged is designated 6061-T6, and 7075 treated in the same manner is 7075-T6. Casting alloy example, 356-T6.
T7	Solution heat treated and then stabilized	Designation applies to products in which the temperature and time conditions for stabilizing are such that the alloy is carried beyond the point of maximum hardness, providing control of growth or residual stress, or both (2018-T71, 4032-T72, 355-T71).
T8	Solution heat treated, cold worked, then artificially aged	Designation applies when the cold working is done for the purpose of improving strength (2011-T8, Alclad 2024-T86), and also when the cold working effect of flattening or straightening is recognized in applicable specifications (Alclad 2024-T81 flat sheet).
T9	Solution heat treated, artificially aged, then cold worked	Wire of 6061 heat treated, artificially aged, and then cold worked 6061-T91.
W	Unstable condition following solution heat treatment	Designation, because of natural aging, is specific only when the period of aging is indicated – for example, 2024-W (1/2 hr), 7075-W (2 months).

[a]Information from ref. 5, pp. 888 and 889.

TABLE A-V. - SPECIAL CONSIDERATIONS FOR NICKEL ALLOYS[a]

Nickel alloy	Special considerations
Inconel alloy 600: Ni 15 Cr 7 Fe	Contact with sulfur-containing atmospheres at elevated temperatures should be avoided.
Inconel alloy 702: Ni 15 Cr 3 Al 0.5 Ti	Contact with sulfur-containing atmospheres at elevated temperatures should be avoided.
Inconel alloy 722: Ni 15 Cr 7 Fe 2.5 Ti 0.7 Al	Solution treating of this alloy at high temperatures (2100° F) should be avoided because subsequent small deformations reduce the high temperature properties. Slow heating of welded parts may result in cracking.
Inconel alloy 718: Ni 19 Cr 17 Fe 5 Cb 3 Mo 0.8 Ti 0.6 Al	Outstanding weld characteristics are due largely to slow response to aging, which keeps restraints to a minimum and avoids buildup of welding stresses. Material is outstanding over a wide range of temperatures in fatigue and fatigue crack propagation; hence, it is useful in applications involving large temperature changes, especially if sub-zero temperature are involved (e.g., rocket motor parts and supersonic aircraft parts). Because of iron content (which contributes to the outstanding weld characteristics) strength at high temperatures is lower than other nickel base superalloys; hence, its usefulness is restricted to a lower maximum temperature than other nickel base super-alloys. Elevated temperature notch sensitivity of the alloy under creep conditions, while not completely understood, is related to the thermal and mechanical history. High finish forging temperature contributes to notch embrittlement. To avoid embrittlement one producer, the Special Metals Corporation speaking of Udimet 718, recommends that the forging be started at 2050° F (max.) and finished at approximately 1750° F. The last 30 percent of reduction should be below 1900° F, preferably below 1850° F. They recommend a maximum solution temperature of 1750° F. They also believe that notch embrittlement can best be evaluated at 1200° F, 100 ksi rather than the more commonly used condition 1300° F, 75 ksi for evaluating notch embrittlement due to thermomechanical history.
Inconel alloy X-750: Ni 15 Cr 7 Fe 25 Ti 1 Cb 0.7 Al	Avoid heating in sulfur containing atmospheres. Dimensional changes on aging require attention.

[a]From information in ref. 6, secs. 41XX and 42XX.

TABLE A-V. - Continued. SPECIAL CONSIDERATIONS FOR NICKEL ALLOYS[a]

Nickel alloy	Special considerations
Monel alloy K-500: Ni 29 Cu 3 Al 0.5 Ti	Welding of this alloy requires special considerations to avoid degradation of soundness and mechanical properties in the weld area. Alloy may be welded by the oxyacetylene, inert gas tungsten arc, or metallic arc processes, using proper filler rods. Oxyacetylene flame should be kept strongly reducing, and the heated end of the filler rod should be kept in the protective atmosphere of the flame to avoid oxidizing the rod. Number 44 K-Monel gas welding wire should be used with a paste flux. For metallic arc welding, number 34 K-Monel rod should be used in a shielded arc. Welding should be performed on annealed material and the welded assembly stress relieved before aging. The welded assembly should be taken through the age hardening range as quickly as possible.
Incoloy alloy 901: Ni 35 Fe 13 Cr 6 Mo 2.5 Ti	Heating in sulfur-containing atmospheres should be avoided. Forgings in this alloy exhibit a pronounced directionality.
713 LC Ni 12 Cr 6 Al 4.5 Mo 2 Cb 0.7 Ti	The developments of steep thermal gradients in large components such as turbine wheels during cooling from casting or heat treatment at high temperature (2150° F) can introduce extremely high residual stresses which must either be eliminated or allowed for in selection of service stresses. The simplest method of reducing these stresses during heat treatment is by reducing cooling rates combined with methods of minimizing section size temperature difference by padding with insulating material.
Hastelloy C: Ni 16 Cr 16 Mo 5 Fe 4 W	This alloy is very sensative to overheating on solution treating. Both its strength and its corrosion resistance may be impared when heated to 2285° F or higher.
TD Nickel Ni 2 ThO$_2$	The radiation levels experienced during handling and during fabrication of the alloy are well below the AEC established tolerances. Although the special merit of the alloy is reflected by its retention of strength at high temperatures for long service periods, it must be protected from oxidation by suitable coating or cladding. Because the alloy achieves a major component of strength from the cold work induced during processing, its strength is very sensitive to test direction. Caution should be exercised in use to insure that the principal loads are supported by material oriented in the major working direction. Directionality of strength is reflected in shear strengths measured in direction of principal deformation. Care should be exercised to avoid introduction of shear loads in weak directions. Joining by welding or other processes involving high temperature, especially in the presence of foreign elements or alloys, can seriously degrade long-time properties even if short-time tensile strengths are retained.

[a]From information in ref. 6, secs. 41XX and 42XX.

TABLE A-V. - Continued. SPECIAL CONSIDERATIONS FOR NICKEL ALLOYS[a]

Nickel alloy		Special considerations
713C:		Control of cleanliness and properties is inadequate for air castings.
	Ni	Although alloy is not intended for welding, improved weldability can be obtained by maintaining low aluminum content. Improved high temperature properties, thermal shock, and impact resistance can be achieved by directional solidification. Material prepared from pre-alloy powders has improved tensile strength properties up to about 1400° F, and superplasticity properties above approximately 1900° F, thus rendering the forming properties very easy at this temperature or above. Heat treatment after forming can remove superplasticity characteristics at high temperature while retaining a strength advantage over the cast form up to 1400° F, and only minor loss in strength above this temperature.
13	Cr	
6	Al	
4	Mo	
2	Cb	
0.7	Ti	
Rene 41:		A major problem in the use of this alloy has been the occurrence of cracking during the heat treatment of welded parts. Recent developments have, however, provided major directions toward the solution of this problem. Two basic approaches have been developed. One is the overaging treatment prior to welding followed by standard heat treatment after welding; the other is solution treating prior to welding with controlled cooling after solution treatment. Weld patch tests have also been developed to identify heats that have high susceptibility to weld cracking.
	Ni	
19	Cr	
11	Co	
10	Mo	
3	Ti	
1.5	Al	Recent studies on sheet have indicated that under certain conditions the alloy may become highly notch sensitive in creep rupture tests. The reason for this behavior is not completely understood.
TD NiCr:		Considerable scatter characterizes the reported strength values for TD NiCr sheet and foil at both room and elevated temperature. The producer's specified properties for thermomechanically processed sheet are at the lower end of the scatter band at room temperature and near the midpoint at elevated temperatures. It is likely that the specified minimum properties will change with the further development of the alloy.
	Ni	
18	Cr	
2	ThO_2	Processing conditions producing high strength at elevated temperatures result in low values of tensile elongation for sheet and low reduction in area values for bar. At 2200° F, creep rupture specimens of thermomechanically processed materials exhibit essentially zero elongation. Mild notch tests on sheet with an unspecified processing history exhibited notch weakening at 2200° F. The significance of these low values of ductility on the fracture toughness should be determined by suitable tests using specimens containing fatigue cracks. Material which has been cold worked or thermomechanically processed to obtain high strength at elevated temperatures exhibits considerable directionality with the transverse direction being of lower strength in tensile and creep rupture tests.
		TD NiCr is slightly radioactive due to the ThO_2 content. It is an alpha emitter and requires precautions be taken if dust is generated by dry grinding.
Inconel alloy 700:		Contact with sulfur containing atmospheres at elevated temperatures should be avoided. Overheating and lack of lubrication during forging will cause cracks and checks.
	Ni	
30	Co	
15	Cr	
3	Al	
3	Mo	
2	Ti	

[a]From information in ref. 6, secs. 41XX and 42XX.

Nickel alloy		Special considerations
Waspaloy:		Solution treating in an oxidizing atmosphere may result in intergranular oxidation. There is limited information available which indicates that the alloy may become embrittled upon long time exposure to stress in an oxidizing atmosphere.
	Ni	
20	Cr	
14	Co	Sharp notch embrittlement in creep has been observed at temperatures of 1000° and 1200° F for both solution treated and aged and cold rolled and aged sheet. These are insufficient data to establish the time-temperature dependence of this embrittlement. However, the effects appear to be larger at 1200° F than 1000° F for the solution treated and aged sheet. The cold rolled and aged material exhibits considerable notch embrittlement at both test temperatures at rupture times between 10 and 1000 hours, with the transverse direction being considerably more notch sensitive than the longitudinal direction. Sharp notch brittleness is also observed for cold rolled and aged sheet following an exposure to 650° or 1000° F at 40 ksi for 1000 hours. The effect is considerably larger at 1000° F than at 650° F. Similar exposure conditions produce no embrittlement for solution treated and aged sheet.
4	Mo	
3	Ti	
1	Al	
Mar-M-200:		Freckles have been observed in directionally solidified polycrystalline and monocrystalline materials. It has been determined that such freckles are linear assemblies of small random equiaxed grains which are enriched in all but the inversely segregated solute species. Excessive interdendritic porosity and feeding shrinkage are observed in the vicinity of a freckle line. Freckling tendency varies with solidification and alloy composition. Freckles degrade physical properties, and must be avoided.
	Ni	
12.5	W	
10	Co	
9	Cr	
5	Al	
2	Ti	The PWA 1422 alloy containing 2 percent hafnium provides increased transverse ductility and creep rupture strength in thin sections. A minimum in elongation characterizes the test temperature range between 1400° and 1600° F.
1	Cb	
+	B	
+	Zr	
IN-100:		Because of the low chromium content, as well as the presence of vanadium, oxidation resistance is not adequate at the high temperatures where the strength of the alloy assumes special advantage. The problem is usually overcome by the use of aluminum or aluminum-base coatings. Many of these are proprietary, and the compositions as well as heat treatments are not revealed. Information provided by the coating produces shows beneficial effects of coatings as protection against oxidation and sulfidation and improvement of thermal shock resistance. These benefits are apparently obtained without impairing the tensile and creep properties at high temperature. The high hardener content of the alloy make it particularly prone to the precipitation of embrittling phases, such as sigma, upon prolonged exposure to high temperature, especially if stress is simultaneously applied. Special compositions, low in titanium content, have been found advantageous for avoiding such embrittlement. The International Nickel Company, original developer of IN-100, has developed a modification designated as IN-731X, and the General Electric Company has developed René 100 for this purpose. Both use the Pha Comp techniques, wherein electron vacancy of the remaining matrix after the major hardening precipitates have formed is used as a basis for the determination of whether sigma will form. Every heat requires a separate computation to determine sigma-proneness because of the large variations permitted in the chemistry of individual heats; however, in general, the revised composition limits with lower titanium contents are usually sigma-free within the specified limits of the other elements. The tendency toward sigma-proneness was first reported to be a
	Ni	
15	Co	
9.5	Cr	
5.5	Al	
5	Ti	
3	Mo	
0.95	V	
0.015	B	

[a]From information in ref. 6, secs. 41XX and 42XX.

TABLE A-V. – Concluded. SPECIAL CONSIDERATIONS FOR NICKEL ALLOYS[a]

Nickel alloy	Special considerations
	result of exposure to high temperatures for long times, especially at stress. It was also shown that sigma formed at 1650° F could be solutioned at 1900° to 2000° F, in 2 to 4 hours and that a 2000° F, 2-hour heat treatment delayed sigma formation. This heat treatment was observed to delay sigma formation whether applied to an as-cast bar or whether applied to a bar previously exposed to 1650° F containing sigma. This observation points to the possibility of beneficial effects of heat treatment, in contrast to the normally used as-cast structure. It also points to the possibility of removing creep damage by reheat treatment for this alloy.
Udimet 700: Ni 18 Co 15 Cr 5 Mo 4.5 Al 3.5 Ti 0.03 B	Special note should be made of recent developments to avoid sigma phase formation using the Pha Comp procedure and of modifications in composition and heat treatment resulting in optimization of properties.

[a]From information in ref. 6, secs. 41XX and 42XX.

59

TABLE A-VI. – PROPERTIES AND APPLICATIONS OF COPPER AND COPPER ALLOYS[a]

Alloy name	Number	Nominal composition, percent	Fabricating characteristics	Typical applications
Oxygen-free copper	102	99.95 Cu	Excellent hot and cold workability; good forgeability. Fabricated by coining, coppersmithing, drawing and upsetting, hot forging and pressing, spinning swaging, stamping.	Gaskets
Electrolytic tough pitch copper	110	99.90 Cu 0.04 O	Fabricating characteristics same as alloy 102.	Gaskets
Silver-bearing tough pitch copper	113, 114, 116	99.90 Cu 0.04 O Ag(e)	Fabricating characteristics same as alloy 102.	Gaskets, chemical process equipment
Phosphorus deoxidized copper, high residual phosphorus	122	99.90 Cu 0.02 P	Fabricating characteristics same as alloy 102.	Lines; plumbing pipe and tubing, condenser tubing, evaporator, and heat exchanger tubing
Beryllium copper	172	99.5 Cu 1.9 Be 0.20 Co	Excellent hot workability. Commonly fabricated by blanking, drawing, forming, and bending, turning, drilling, tapping.	Bellows, bourdon tubing, diaphragms, fuse clips, fasteners, lock washers, springs, switch parts, roll pins, valves, welding equi-- equipment
Gilding 95 percent	210	95.0 Cu 5.0 Zn	Excellent cold workability, good hot workability for blanking, coining, drawing, piercing and punching, shearing, spinning, squeezing and swaging, stamping.	Screws, rivets
Commercial bronze, 50 percent	220	90.0 Cu 10.0 Zn	Fabricating characteristics same as alloy 210 plus heading and upsetting, roll threading and knurling, hot forging and pressing.	Screws, rivets
Red brass, 85 percent	230	85.0 Cu	Fabricating characteristics same as alloy 210.	Condenser and heat exchanger tubing, plumbing pipe
Low brass, 80 percent	240	80.0 Cu 20.0 Zn	Excellent cold workability. Fabrication characteristics same as alloy 210.	Bellows, pump lines, flexible hose
Cartridge brass, 70 percent	260	70.0 Cu 30.0 Zn	Excellent cold workability. Fabricating characteristics same as alloy 240, except for coining, roll threading and knurling.	Radiator cores and tanks, fasteners, hinges, plumbing accessories, pins, rivets
Yellow brass	268, 270	65.0 Cu	Excellent cold workability. Fabricating characteristics same as alloy 240.	Same as alloy 260
Muntz metal	280	60.0 Cu 40.0 Zn	Excellent hot formability and forgeability for blanking, forming and bending, hot forging and pressing, hot heading and upsetting, shearing.	Architectural, large nuts and bolts, brazing rod, condenser plates, condenser, evaporator and heat exchanger tubing, hot forgings
Leaded commercial bronze	314	89.0 Cu 1.75 Pb 9.25 Zn	Excellent machinability.	Screws, machine parts
Low-leaded brass tube	330	66.0 Cu 0.5 Pb 33.5 Zn	Combines good machinability and excellent cold workability. Fabricated by forming and bending, machining, piercing and punching.	Pump and power cylinders and liners
High-leaded brass tube	332	66.0 Cu 1.6 Pb 32.4 Zn	Excellent machinability. Fabricated by piercing, punching, and machining.	General purpose screw machine parts
Low-leaded brass	335	65.0 Cu 0.5 Pb 34.5 Zn	Similar to alloy 332. Commonly fabricated by blanking, drawing, machining, piercing and punching, and stamping.	Butts, hinges
Medium-leaded brass	340	65.0 Cu 1.0 Pb 34.0 Zn	Similar to alloy 332. Fabricated by blanking, heading and upsetting, machining, piercing and punching, roll threading and knurling, stamping.	Butts, gears, nuts, rivets, screws

[a]From ref. 7, pp. 26 and 27.

Alloy name	Number	Nominal composition, percent	Fabricating characteristics	Typical applications
High-leaded brass	342, 353	65.0 Cu 2.0 Pb 33.0 Zn	Fabricating characteristics same as alloy 340.	Clock plates and nuts, gears, wheels and channel plate
Extra-high-leaded brass	356	63.0 Cu 2.5 Pb 34.5 Zn	Excellent machinability. Fabricated by blanking, machining, piercing and punching, stamping.	Same as alloys 342 and 353
Free-cutting brass	360	61.5 Cu 3.0 Pb 35.5 Zn	Excellent machinability. Fabricated by machining, roll threading and knurling.	Gears, pinions, automatic high speed screw machine parts
Leaded muntz metal	365 to 368	60.0 Cu 0.6 Pb 39.4 Zn	Combines good machinability with excellent hot formability.	Condenser tube plates
Free-cutting muntz metal	370	60.0 Cu 1.0 Pb 39.0 Zn	Fabricating characteristics similar to alloys 365 to 368.	Automatic screw machine parts
Forging brass	377	59.0 Cu 2.0 Pb 39.0 Zn	Excellent hot workability. Fabricated by heading and upsetting, hot forging and pressing, hot heading and upsetting, machining.	Forgings and pressings of all kinds
Inhibited admiralty	443, 444, 445	71.0 Cu 28.0 Zn 1.0 Sn	Excellent cold workability for forming and bending.	Condenser, evaporator and heat exchanger tubing, condenser tubing plates, distiller tubing, ferrules.
Naval brass	464 to 467	60.0 Cu 39.25 Zn 0.75 Sn	Excellent hot workability and hot forgeability. Fabricated by blanking, drawing, bending, heading and upsetting, hot forging, pressing.	Aircraft turnbuckle barrels, balls, bolts, nuts, rivets, valve stems, condenser plates, welding rod
Leaded naval	485	60.0 Cu 1.75 Pb 37.5 Zn 0.75 Sn	Combines excellent hot forgeability and machinability. Fabricated by hot forging and pressing, machining.	Marine hardware, screw machine parts, valve stems
Phosphor bronze, 1.25-percent E	505	98.75 Cu 1.25 Sn Trace P	Excellent cold workability, good hot formability. Fabricated by blanking, bending, heading and upsetting, shearing and swaging.	Flexible hose
Phosphor bronze, 5-percent A	510	95.0 Cu 5.0 Sn Trace P	Excellent cold workability. Fabricated by blanking, drawing, bending, heading and upsetting, roll threading and knurling, shearing, stamping.	Bellows, bourdon tubing, clutch disks, cotter pins, diaphragms, fasteners, lock washers, wire brushes, chemical hardware, welding rod
Phosphor bronze, 8-percent C	521	92.0 Cu 8.0 Sn Trace P	Good cold workability for blanking, drawing, forming and bending, shearing, stamping.	Generally for more severe service conditions than alloy 510
Phosphor bronze, 10-percent D	524	90.0 Cu 10.0 Sn Trace P	Good cold workability for blanking, forming and bending shearing.	Heavy bars and plates for severe compression, bridge and expansion plates and fittings articles requiring good spring qualities, resiliency, fatigue resistance, good wear and corrosion resistance

[a]From ref. 7, pp. 26 and 27.

Alloy name	Number	Nominal composi- tion, percent	Fabricating characteristics	Typical applications
Free-cutting phosphor bronze	544	88.0 Cu 4.0 Pb 4.0 Zn 4.0 Sn	Excellent machinability, good workability. Fabricated by blanking, drawing, bending, machining, shearing, stamping.	Bearings, bushings, gears, pinions shafts, thrust washers, valve parts
Aluminum bronze, D	614	91.0 Cu 7.0 Al 2.0 Fe	Fabricated by blanking, drawing, forming and bending, heading and roll threading.	Nuts, bolts, stringers and threaded members, corrosion resistant vessels and tanks, structural components, machine parts and members, condenser tubing and pipe, protective sheathing and fastening
Low-silicon bronze, B	651	98.5 Cu 1.5 Si	Excellent hot and cold workability. Fabricated by forming and bending, heading and upsetting, hot forging and pressing, roll threading and knurling, squeezing and swaging.	Hydraulic pressure lines, anchor screws, bolts, cable clamps, cap screws, machine screws, nuts, rivets, U-bolts, electrical conduits, heat exchanger tubing, welding rod
High-silicon bronze, A	655	97.0 Cu 3.0 Si	Excellent hot and cold workability. Fabricated by blanking, drawing, forming and bending, heading and upsetting, hot forging and pressing, roll threading and knurling, shearing, squeezing and swaging.	Similar to alloy 651
Manganese bronze, A	675	58.5 Cu 1.4 Fe 39.0 Zn 1.0 Sn 0.1 Mn	Excellent hot workability. Fabricated by hot forging and pressing, hot heading and upsetting.	Clutch disks, pump rods, shafting, balls, valve stems and bodies
Aluminum brass	687	77.5 Cu 20.5 Zn 2.0 Al	Excellent cold workability for forming and bending.	Same as alloys 443, 444, and 445.
Copper nickel, 10 percent	706	88.7 Cu 1.3 Fe 10.0 Ni	Good hot and cold workability. Fabricated by forming and bending, welding.	Condensers, condenser plates, evaporator and heat exchanger tubing, ferrules
Copper, nickel, 30 percent	715	70.0 Cu 30.0 Ni	Similar to alloy 706.	
Nickel silver, 65-10	745	65.0 Cu 25.0 Zn 10.0 Ni	Excellent cold workability. Fabricated by blanking, drawing, etching, forming and bending, heading and upsetting, roll threading and knurling, shearing, spinning, squeezing and swaging.	Rivets, screws, slide fasteners
Nickel silver, 65-18	752	65.0 Cu 17.0 Zn 18.0 Ni	Fabricating, characteristics similar to alloy 745.	Rivets, screws
Nickel silver, 65-15	754	65.0 Cu 20.0 Zn 15.0 Ni	Fabricating characteristics similar to alloy 745.	
Nickel silver, 65-12	757	65.0 Cu 23.0 Zn 12.0 Ni	Fabricating characteristics similar to alloy 745.	
Nickel silver, 55-18	770	55.0 Cu 27.0 Zn 18.0 Ni	Good cold workability. Fabricated by blanking forming and bending and shearing.	Springs and resistance wire

[a]From ref. 7, pp. 26 and 27.

TABLE A-VII – PROPERTIES AND USES FOR HEAT TREATABLE COPPER ALLOYS[1]

	Beryllium Copper (Strip) CDA 172	Copper-Nickel-Silicon (Strip) CDA 647	Chromium Copper (Strip) CDA 182	Zirconium Copper (Strip) CDA 150	Copper-Nickel-Phosphorus CDA 190
Nominal composition, %	97.85 Cu, 1.90 Be, 0.25 Co	97.50 Cu, 1.90 Ni, 0.60 Si	99.10 Cu, 0.90 Cr	99.85 Cu, 0.15 Zn	97.55 Cu, 1.20 Ni, 0.25 P
Properties					
Tensile strength, psi					
Soft (SA)*	69,000	41,000	30,000	32,000	38,000
SA + HT	177,000	85,000	56,000	34,000	65,000
1 2 hard	92,000	48,000	43,000	48,000	61,000
1 2 hard + HT	195,000	91,000	62,000	53,000	82,000
Hard	110,000	58,000	52,000	55,000	66,000
Hard + HT	200,000	98,000	67,000	59,000	90,000
Yield strength, psi					
Soft (SA)	32,000	14,000	8,000	14,000	10,000
SA + HT	155,000	65,000	45,000	18,000	40,000
1 2 hard	82,000	46,000	40,000	46,000	54,000
1 2 hard + HT	175,000	81,000	57,000	45,000	71,000
Hard	104,000	57,000	51,000	53,000	59,000
Hard + HT	180,000	85,000	63,000	53,000	78,000
Elongation in 2 in., %					
Soft (SA)	47	39	42	51	40
SA + HT	7	16	15	51	33
1 2 hard	10	17	7	11	8
1 2 hard + HT	3	13	9	18	6
Hard	4	3	2	7	6
Hard + HT	2	9	6	14	4
Electrical conductivity, % IACS					
Soft (SA)	18	23	36	70	32
SA + HT	24	40	81	84	60
1 2 hard	16	23	35	72	32
1 2 hard + HT	24	40	78	88	60
Hard	16	23	35	73	32
Hard + HT	24	40	78	88	60
Thermal conductivity, Btu sq ft/ft/hr/°F					
Soft (SA)	46	58	90	167	80
SA + HT	61	100	189	195	145
1 2 hard	43	58	88	171	80
1 2 hard + HT	61	100	183	202	145
Hard	43	58	88	173	80
Hard + HT	61	100	183	202	145
Fabricating Characteristics					
Hot working temperature (SA or HT)	1050 to 1475 F	1300 to 1375 F	1650 to 1695 F	1650 to 1760 F	1300 to 1550 F
Solution annealing temperature	1400 to 1475	1375 to 1475	1830	1650 to 1750	1300 to 1450
Aging temperature (1 to 2 hr)	600	800 to 900	850 to 930	750 to 950	800 to 900
Machinability rating, (SA, CW, HT)†	20%	30%	20%	20%	30%
Cold workability	Good	Excellent	Good	Excellent	Excellent
Hot workability	Excellent	Excellent	Good	Excellent	Excellent
Joining Characteristics					
Soft soldering	Excellent	Excellent	Excellent	Excellent	Excellent
Silver brazing	Good	Excellent	Excellent	Excellent	Excellent
Oxyacetylene welding	Poor	Good	—	Fair to good	Good
Carbon arc welding	Excellent	Fair to poor	—	Fair	Good
Gas shielded arc welding	Good	Good	—	Good	Good
Resistance welding	Excellent	Good	—	Not recommended	Fair
Typical Applications					
	Diaphragms, bellows, relays, circuit breakers, switches; fuse and component holders; cantilever flat springs; Belleville, curved spring and wavy spring washers; brush springs used at ambient temperature up to 300 F	Fasteners, electrical parts, marine hardware, resistance welded assemblies, resistance welding tip holders, rotors and rings, springs, switch gear, wire connectors, wire forms and wire products	Similar to coppers, such as circuit breakers, parts where high strength and high thermal and electrical conductivity are needed. Used where higher softening point than that provided by copper is needed	Commutator segments, conductors, electrical parts, gaskets, resistance welding tips, rotor bars and plates, switch parts, washers, wave guides, wire forms and wire products	Springs, clips, electronic parts, high strength electrical connectors, bolts, nails, screws, rivets, fasteners

Note: Data Sheet lists only those alloys containing 97% Cu (min).
*SA, solution annealed; CW, cold worked; HT, aged. †Based on 100% for free-cutting brass (CDA 360).

[1] From ref. 7, p. 25.

REFERENCES

In parentheses after most references are given the Microfiche card numbers denoting the location of the references in the Microfiche supplement and the pages of the references reproduced in the Microfiche supplement.

1. Smith, H. H.; and Shahinian, P.: Effect of Oxygen and of Water Vapor on the Fatigue Life of Nickel at 300 C. Effects of Environment and Complex Load History on Fatigue Life. Spec. Tech. Publ. No. 462, ASTM, 1970, pp. 217-233.

2. Davis, Harmer E.; Troxell, George E.; and Wiskocil, Clement T.: The Testing and Inspection of Engineering Materials. Second ed., McGraw-Hill Book Co., Inc., 1955.

3. White, E. L.; and Ward, J. J.: Ignition of Metals in Oxygen. DMIC Rep. 224, Battelle Memorial Inst., Feb. 1, 1966. (Card 1: pp. i, ii, 6-16, A1-A3.)

4. Nihart, G. J.; and Smith, C. P.: Compatibility of Materials With 7500 PSI Oxygen. Union Carbide Corp. (AMRL-TDR-64-67, AD-608260), Oct. 1964. (Card 1: pp. v, 8, 32-34.)

5. Lyman, Taylor, ed.: Metals Handbook. Vol. I. Properties and Selection of Metals. Eighth ed., Am. Soc. Metals, 1961.

6. Wolf, J.; and Brown, W. F., Jr., eds.: Aerospace Structural Metals Handbook. Vols. 1, 2, and 3. Stulen, Inc. (AFML-TR-68-115), 1972.

7. Anon.: Metal Progress Materials and Process Engineering Data Book. Am. Soc. Metals, 1968. (Most recent available edition at time of writing, 1970 edition.) (Card 1: pp. 1-14, 25-27.)

8. Shank, M. E., ed.: Control of Steel Construction to Avoid Brittle Failure. Welding Research Council, 1967.

9. Sisco, Frank T.: Engineering Metallurgy. Pitman Publ. Co., 1957.

10. Anon.: 1971 Annual Book of ASTM Standards. Part 31. ASTM, 1971.

11. Anon.: ASME Boiler and Pressure Vessel Code. Section VIII. Rules for Construction of Pressure Vessels. Divisions 1 and 2. ASME, 1971.

12. Wigley, D. A.: Mechanical Properties of Materials at Low Temperatures. Plenum Press, 1971.

13. Anon.: Low Temperature and Cryogenic Steels. Materials Manual. United States Steel. (Cards 1 and 2: pp. 5-81.)

14. Van Horn, Kent R., ed.: Aluminum. Vol. II. Design and Application. Am. Soc. Metals, 1967.

15. Dean, L. E.; and Thompson, W. R.: Ignition Characteristics of Metals and Alloys. ARS J., vol. 31, no. 7, July 1961. (Card 2: pp. 917-923.)

16. Van Horn, Kent R., ed.: Aluminum. Vol. III. Fabrication and Finishing. Am. Soc. Metals, 1967.

17. Anon.: SAE Handbook. Soc. Automotive Eng., 1969.

18. Key, C. F.; and Riehl, W. A.: Compatibility of Materials with Liquid Oxygen. NASA TM X-985, 1964.

19. Touloukian, Y. S.: Thermophysical Properties of High Temperature Solid Materials. Vol. 2. Parts I and II. MacMillian Co., 1966.

20. Hust, J. G.; Powell, Robert L.; and Weitzel, D. H.: Thermal Conductivity, Electrical Resistivity and Thermopower of Aerospace Alloys From 4 to 300 K. Rep. 9732, National Bureau of Standards (NASA CR-108088), June 9, 1969.

21. Eldridge, E. A.; and Deem, H. W.: Report on Physical Properties of Metals and Alloys from Cryogenic to Elevated Temperatures. Spec. Tech. Publ. No. 296, ASTM, 1961. (Cards 2 and 3: pp. iii, 5-32.)

22. Coston, R. M.: Handbook of Thermal Design Data for Multilayer Insulation Systems. Vol. II. Rep. LMSC-A847882, Vol. II, Lockheed Missiles and Space Co. (NASA CR-87485), June 25, 1967. (Card 3: pp. 2-1 - 2-7, 2-9 - 2-13, 2-15, 2-17, 2-19 - 2-21, 2-23, 2-25, 2-27 - 2-29, 2-31, 2-33 - 2-35, 2-37, 2-39 - 2-41, 2-43, 2-45 - 2-49, 2-51.)

23. Schwartzberg, Fred H.; Osgood, Samuel, H.; Bryant, Carol; and Knight, Marvin: Cryogenic Materials Data Handbook. Rep. AFML-TDR-64-280, Air Force Materials Lab. July 1970.
    Vol. I (AD-713619) -- Sections A, B, and C. (Card 3: pp. 42, 43, 75, 96, 97, 176, 204, 227, 238, 246.)
    Vol. II (AD-713620) -- Sections D, E, F, G, H, and I. (Card 3: pp. 13, 14, 25, 41, 55, 81, 144, 226.)

24. Van Horn, Kent R., ed.: Aluminum. Vol. I. Properties, Physical Metallurgy and Phase Diagrams. Am. Soc. Metals, 1967.

25. Rosenberg, Samuel J.: Nickel and Its Alloys. Monograph 106, National Bureau of Standards, May 1968. (Card 3: pp. 56-61.)

26. Keuhl, D. K.; and Zwillenberg, M. L.: Investigation of the Ignition and Combustion of Metal Wires. Rep. F910336-24, United Aircraft Research Lab. (NASA CR-89788), May 1967.

27. Browning, Ethel: Toxicity of Industrial Metals. Second ed., Butterworths & Co., 1969.

28. Reynolds, W. C.: Investigation of Ignition Temperatures of Solid Metals. NASA TN D-182, 1959. (Card 4: All.)

29. Glassman, I.; Mellor, A. M.; Sullivan, H. F.; and Laurendeau, N. M.: A Review of Metal Ignition and Flame Models. Reactions between Gases and Solids. Conf. Proc. No. 52, AGARD, Feb. 1970. (Cards 4 and 5: pp. 19-1 - 19-30, 19-App-1 - 19-App-9.)

30. Carslaw, H. S.; and Jaeger, J. C.: Conduction of Heat in Solids. Clarendon Press, 1950.

31. Arpaci, Vedat S.: Conduction Heat Transfer. Addison-Wesley Publ. Co., 1966.

BIBLIOGRAPHY

Anon.: ALCOA Structural Handbook. Aluminum Company of America, 1960.

Anon.: Behavior of Materials at Cryogenic Temperatures. Spec. Tech. Publ. No. 387, ASTM, 1966.

Anon.: Evaluation of Metallic Materials in Design for Low Temperature Service. Spec. Tech. Publ. No. 302, ASTM, 1962.

Anon.: Low Temperature Mechanical Properties of Various Alloys. NASA SP-5921(01), 1970.

Anon.: Military Standardization Handbook - Metallic Materials and Elements for Aerospace Vehicle Structures, Two Volumes, MIL-HDBK-5B, Sept. 1, 1971.

Anon.: The Mechanical Properties of Copper-Beryllium Alloy Strip. Spec. Tech. Publ. No. 367, ASTM, 1964.

Bell, Joseph H., Jr.: Cryogenic Engineering. Prentice-Hall, Inc., 1963.

Boyd, G. M., ed.: Brittle Fracture in Steel Structures. Butterworth & Co., 1970.

Christian, J. L.: Evaluation of Materials and Test Methods at Cryogenic Temperatures. Rep. ERR-AN-400, General Dynamics/Astronautics, Dec. 10, 1963.

Frank, Robert G.; and Zimmerman, William F.: Materials for Rockets and Missiles. MacMillan Co., 1959.

Groenveld, T. P.; et al.: High-Strength Steel 9Ni-4Co - Processes and Properties Handbook. Battelle Memorial Inst., Apr. 1968.

Martin, H. L.; et al.: Effects of Low Temperatures on the Mechanical Properties of Structural Metals - Revised and Enlarged Edition. NASA SP-5012(01), 1968.

Parker, Earl R., ed.: Materials for Missiles and Spacecraft. McGraw-Hill Book Co., Inc., 1963.

Sessler, J., and Weiss V.: Materials Data Handbook(s):
   Aluminum Alloy 2014. NASA Tech. Support Pkg. 67-10089, Apr. 1966.
   Aluminum Alloy 2219. NASA Tech. Support Pkg. 67-10089, Mar. 1966.
   Aluminum Alloy 5456. NASA Tech. Support Pkg. 67-10089, May 1966.
   Aluminum Alloy 6061. NASA Tech. Support Pkg. 69-10065, June 1969.
   Inconel Alloy 718. NASA Tech. Support Pkg. 67-10282, Sept. 1966.
   Type 301 Stainless Steel, NASA Tech. Support Pkg. 67-10089, June 1966.

Touloukian, Y. S., ed.: Recommended Values of the Thermophysical Properties of Eight Alloys, Major Constituents and Their Oxides. Purdue University, Feb. 1966.

Varley, P. C.: The Technology of Aluminum and its Alloys. CRC Press, 1970.

Williams, L. R.; Schmidt, E. H.; and Young, J. D.: Design and Development Engineering Handbook of Thermal Expansion Properties of Aerospace Materials at Cryogenic and Elevated Temperatures. Rep. R-6981, North American Aviation (NASA CR-102331), Mar. 30, 1969.

Wood, R. A.: A New Aluminum Sand Casting Alloy of High Toughness (M-45). SP-5091, 1970.